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Air/Superfund National Technical Guidance Study Series. Volume 2 Estimation of Baseline Air Emissions at Superfund Sites (Revised)

Radian Corp., Austin, TX

Prepared for:

Environmental Protection Agency, Research Triangle Park, NC

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This report presents available methods for estimating air emissions at Superfund hazardous waste sites prior to any remedial action. Methods described include direct emission measurement techniques, indirect measurements and predictive emissions modeling. Information is provided on selecting from among the range of methods available given the associated range of costs and uncertainties. This report revises and expands an earlier report, Procedures For Conducting Air Pathway Analyses For Superfund Activities, Volume II, Estimation Of Baseline Air Emissions At Superfund Sites, EPA-450/1-89-002. It is one in a series of reports that provide guidance on conducting air pathway analysis at Superfund hazardous waste sites.

The purpose of this report is to assist EPA Air and Superfund staff, State Air Superfund program staff, Federal and State remedial and removal contractors, potentially responsible parties and others in designing, conducting, and reviewing air pathway analyses at undisturbed hazardous waste sites.

KEY WORDS AND DOCUMENT ANALYSIS

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By

Bart Eklund

and

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Austin, Texas

Contract Number 68-02-4392

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office Of Air and Radiation
Office Of Air Quality Planning And Standards
Research Triangle Park, North Carolina 27711

PREFACE

This report revises and expands an earlier report, Procedures For Conducting Air Pathway Analyses For Superfund Activities, Volume II, Estimation Of Baseline Air Emissions At Superfund Sites, EPA 450/1-89-002. It is one in a series of reports that provide guidance on conducting air pathway analysis at Superfund hazardous waste sites. It was developed for the Office of Air Quality Planning and Standards in cooperation with the Office of Emergency and Remedial Response (Superfund).

This report have been reviewed by the National Technical Guidance Study Technical Advisory Committee, State agencies, various groups within the U.S. Environmental Protection Agency, and the private sector. It provides technical guidance for use by a diverse audience including EPA Air and Superfund Regional and Headquarters staff, State Air Superfund program staff, Federal and State remedial and removal contractors, and potentially responsible parties in analyzing air pathways at hazardous waste sites. This report is written to serve the needs of individuals having different levels of scientific training and experience in designing, conducting and reviewing air pathway analyses. Remedial Project Managers, On Scene Coordinators, and the Regional Air program staff, supported by the technical expertise of their contractors, will use this volume when developing baseline emission estimates for undisturbed hazardous waste sites.

Because assumptions and judgments are required in many parts of an air pathway analysis, an analysis requires a strong technical background in air emission estimation methods, measurements, modeling and monitoring. Air pathway analyses cannot be reduced to simple "cookbook" procedures. Therefore, this volume is designed to be flexible, allowing the use of professional judgment. The procedures presented in this report are intended solely for technical guidance. They are not intended, nor can they be relied upon, to create rights substantive or procedural, enforceable by any party in litigation with the United States.

This edition of Volume II will be periodically updated to incorporate new data and information on air pathway analysis procedures. The Agency reserves the right to act at variance with these procedures and to change them as new information and technical tools become available on air pathway analyses without formal public notice. The Agency will, however, attempt to make any revised or updated manual available to those who currently have a copy through the registration form included with the report.

Copies of this report are available as supplies permit, through the Library Services Office (MD-35), U.S. EPA, MD-35, Research Triangle Park, NC 27711 or from the National Technical Information Services, 5285 Port Royal Road, Springfield, VA 22161.

This report has been reviewed by the Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, and has been approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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GLOSSARY OF FREQUENTLY USED TERMS AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists, 6500 Glenway Ave., Building D-5, Cincinnati, OH 45211.
Adsorption	A physical process in which molecules of gas, dissolved substances, or liquids adhere in an extremely thin layer to the surfaces of solid bodies with which they are in contact.
Air Monitoring	A gas phase sampling technique where ambient air is sampled. It can be used to develop emission rate estimates and is similar to indirect emission measurement except measurements usually are taken at greater distances from the waste site.
APA	Air Pathway Analyses. APA are designed to assess the potential for air emissions from a hazardous waste site.
BEEs	Baseline Emission Estimates. These are estimates of baseline emission rates from a hazardous waste site in its undisturbed conditions.
Calibration	Establishment of a relationship between the response of a measurement system obtained by introducing various calibration standards into the system. The calibration levels should bracket the range of levels for which actual measurements are to be made.
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act of 1980. Modified by SARA in 1986. The Acts created a special tax that goes into a trust fund, commonly known as Superfund, to investigate and clean up abandoned or uncontrolled hazardous waste sites.
Co-disposal Site	A waste site that has received and mixed municipal and hazardous wastes.
Detection Limit	The minimum quantity of a compound which yields a "measureable response." Measurable response has many statistical definitions. Be careful to differentiate "instrumental detection limit," which refers to the minimum quantity of material introducible into a measurement system that can be detected, from "method detection limit," which means the minimum concentration of a compound in a sample which, when put through the entire sampling and analysis process, can be detected.
Direct Emissions Measurement	A measurement made directly on or above the waste to determine the emission rate of volatile species from a liquid or solid surface.

OSHA	Occupational Safety and Health Administration, U.S. Department of Labor.
OVA	Organic vapor analyzer.
Particulate Matter	Airborne solid or liquid matter.
PEL	OSHA permissible exposure limit, expressed as ppm or mg/m^3 of substance in air.
ppb	Parts per billion.
ppm	Parts per million.
Probe	A tube used for gas phase concentration sampling or for measuring pressures at a distance from the actual collection or measuring apparatus.
Quality Assurance	A system of activities designed to assure that the quality control system is performing adequately.
Quality Control	A system of specific efforts designed to test and control the quality of data obtained.
RI	Remedial Investigation. Field investigations of hazardous waste sites to determine pathways and nature and extent of contamination.
RPM	Remedial Project Manager, equivalent to a site manager at non-NPL sites.
Sampling	The process of withdrawing or isolating a fractional part of the whole. In air or gas analysis, it is the separation or a portion of an ambient atmosphere with or without the simultaneous isolation of selected components.
SARA	Superfund Amendments and Reauthorization Act. Modifications of CERCLA enacted on October 17, 1986.
Screening Technologies	Quick and simple methods for estimating baseline emissions.
Undisturbed Condition	The condition in which a hazardous waste site is discovered or may be left if a no-action remedial alternative is selected.
VOCs	Volatile organic compounds. An organic compound (containing carbon) that evaporates (volatilizes) readily at room temperature.

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Mr. Joe Padgett, U.S. EPA OAQPS
Mr. Jim Durham, U.S. EPA OAQPS
Ms. Anne Pope, U.S. EPA OAQPS
Ms. Donna Abrams, U.S. EPA Region III
Ms. Grace Musumeci, U.S. EPA Region III
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SECTION 1
INTRODUCTION

1.1 BACKGROUND

The United States Environmental Protection Agency (EPA) is responsible for the assessment and cleanup of the National Priority List (NPL) sites under CERCLA and SARA. EPA's Remedial Program Managers (RPMs) are required to assess the potential for air emissions and air quality impacts caused by NPL sites prior to and during cleanup. To date, no standard approach for assessing the air pathway at NPL or other hazardous waste sites has been available. As a result, performing air pathway analyses (APA) has been less straightforward than evaluating other pathways such as the impacts on ground water or surface water quality. This manual assists RPMs in determining if an uncontrolled site has the potential for significant air emissions and, if so, how to characterize the baseline air emissions potential from the site.

This volume is one in a series of manuals prepared for EPA to assist its RPMs in the assessment of the air contaminant pathway and developing input data for risk assessment. Volume I (1) of the series provides generalized guidance for addressing air issues throughout the overall Superfund process. This manual (Volume II) provides guidance on developing baseline emission estimates for hazardous waste sites. Baseline emission estimates (BEEs) are defined as emission rates estimated for a site in its undisturbed state. Volume III (2) provides guidance on estimating emissions from cleanup activities, and Volume IV (3) provides guidance on ambient air monitoring and on dispersion modeling. Together these four manuals provide a complete treatment of air issues for superfund applications.

CERCLA and SARA mandate the characterization of all contaminant migration pathways from the waste or hazardous material to the environment and evaluation of the resulting environmental impacts. However, air pathway analyses are often overlooked because many sites have little or no perceptible air emissions in their baseline or undisturbed state. Even low level emissions, however, may be significant if toxic or carcinogenic compounds are present. Also, emissions during clean-up may be much higher than baseline emissions. Emissions of potential concern include volatile and semi-volatile organics, acid gases, particulate matter, and toxics associated with windblown particulate matter such as metals, PCBs and dioxins.

A remedial investigation is typically necessary to provide data on air emissions from the site. These emission can be measured directly, or estimated indirectly from chemical and physical data collected during the RI and used as inputs to predictive models. Remedial investigations (RIs) often include ambient air monitoring to assess baseline air quality impacts from the site, but measurements of emission rates or soil-gas concentrations are less widely employed. An introduction to these techniques is a major emphasis of this manual. Emission rate or soil-gas data can be useful for: 1) identifying "hot spots" e.g. areas of higher than average waste content or pockets of subsurface gases, 2) serving as model inputs (source terms) to estimate ambient air concentrations under meteorological conditions other than those encountered during the RI, and 3) estimating emissions during remediation. For this last use, the air emissions investigation during the RI stage would include emission measurements of both the undisturbed wastes and the exposed or disturbed wastes.

While not strictly part of baseline emission estimates, measurements of emissions from exposed or disturbed wastes can generally be performed during the RI using the same techniques presented in this manual for performing baseline emission measurements. These data along with the BEEs can be used in the procedures outlined in Volume III of this series to help evaluate remediation options, design an engineering approach to the site mitigation, and determine whether air emission control technologies or an air monitoring program may be necessary as part of the remedial alternatives.

1.2 OBJECTIVES

The overall objective of this manual is to assist RPMs or site managers in assessing the impacts on air quality from undisturbed sites. Specifically the manual is intended to:

- Present a protocol for selecting the appropriate level of effort to characterize baseline air emissions.
- Assist site managers in designing an approach for estimating baseline emissions.
- Identify available methods for developing site-specific baseline emission estimates (BEEs).

1.3 APPROACH

To meet the objectives of this program, three steps were undertaken to compile and assess existing information: 1) Conduct a literature search, 2) Perform a survey of key researchers, and 3) Review and evaluate the collected information. This work served as the basis for developing the protocol for estimating air emission factors for remediation presented herein. Each step of the approach is discussed below.

A computer-assisted search of 15 databases was performed to identify published literature of potential interest. Keywords were formulated into a search strategy to identify abstracts related to both baseline and remedial emissions. Approximately 1400 abstracts were reviewed, and over one hundred publications were identified as pertinent and obtained by staff librarians.

The literature search was augmented by a telephone survey to locate and access unpublished data or research in progress. A list of contacts was developed that included regional EPA personnel, employees of EPA research offices, EPA contractors, university researchers, and referrals from those initially contacted. A set of questionnaires was used to put the responses obtained during the phone survey in a standard format.

The collected information was reviewed and evaluated with respect to its applicability to estimating baseline air emissions from NPL and other hazardous waste sites.

1.4 RECOMMENDED USES OF THIS MANUAL

This manual is, to the extent possible, a complete, stand-alone document. It is, however, intended to complement existing guidance manuals for the Superfund program.

This manual has certain limitations:

- The manual is a decision making tool but it is not intended to relieve the site managers of their decision making responsibility.
- The protocol is not a "cookbook" for designing air pathway investigations or for determining BEEs.
- The determination of BEEs for a site will not by itself, yield an assessment of actual or potential air impacts, but it is a useful part of that evaluation process.

The steps in the overall NPL site clean-up process are shown in Figure 1. The primary intended use for this manual (Volume II) is for estimating air impacts as part of the evaluation of the undisturbed site. Therefore the manual's guidance is input to the record of decision (ROD) step, as well as, the RI/FS step.

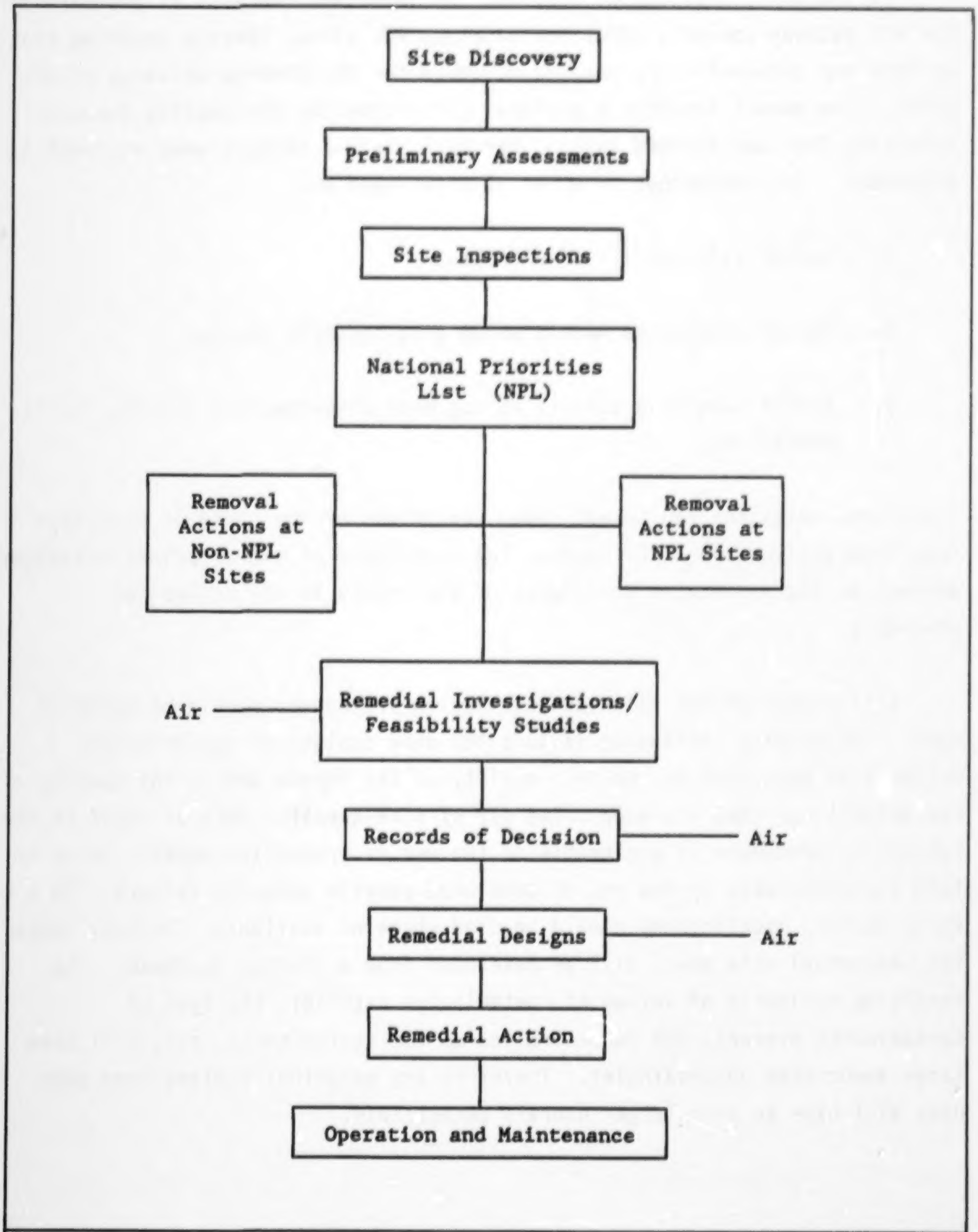
Site Discovery
Preliminary Assessments
Site Inspections
National Priorities List (NPL)
Removal Actions at Non-NPL Sites
Removal Actions at NPL Sites
Air
Remedial Investigations/ Feasibility Studies
Records of Decision
Air
Remedial Designs
Air
Remedial Action
Operation and Maintenance

Figure 1. Superfund Flow Chart, Noting Elements Where This Manual May Apply.

Furthermore, this manual provides the important function of standardizing the air pathway analysis (APA) for baseline NPL sites, thereby ensuring that a uniform and systematic approach is followed for the diverse universe of NPL sites. The manual provides a protocol for estimating air quality impacts resulting from undisturbed sites. For each step, a three-tiered approach is presented. The approaches in order of preference are:

1. Use of site-specific field data;

2. Use of predictive models using site-specific inputs;

3. Use of tabulated default values when site-specific information is unavailable.

Therefore, emissions can be estimated regardless of the state of knowledge regarding a given site. Of course, the confidence of the emissions estimates depends on the associated confidence of the inputs to the estimation procedure.

Limitations of the emissions estimation procedures should be borne in mind. The primary limitation is that the data quality of any emissions estimate is dependent on the data quality of the inputs and on the quality of the assumptions that are made. The use of site-specific data as input to the estimation procedure is preferable to the use of predictive models, which in turn are preferable to the use of tabulated generic emission factors. Data of known quality (confidence) should be used whenever available. In many cases, the conceptual site model will be developed from a limited database. The resulting estimates of volume of contaminated material, the type of contaminants present, the concentration of the contaminants, etc. will have large associated uncertainties. Therefore any emissions derived from such data will have an even larger overall uncertainty.

1.5 DOCUMENT ORGANIZATION

There are five remaining sections to Volume II. General information on the potential for air contaminant emissions from hazardous waste sites is presented in Section 2. Section 3 offers a protocol for determining if BEEs are required and how to develop site-specific BEEs. Information on sampling methods that can be used to obtain BEEs is provided in Section 4. Section 5 describes case studies in which BEEs were needed and/or determined for hazardous waste sites. References are given in Section 6.

An annotated bibliography of the information reviewed for this project is included as Appendix A. Appendix B identifies chemical and physical properties of waste material that may affect is emissions potential. A guide to developing an overall emission rate from individual emission rate measurements is included as Appendix C. Information on databases containing potential input values for predictive models is given in Appendix D. Descriptions of remote sensing systems are contained in Appendix E.

SECTION 2

AIR EMISSIONS FROM HAZARDOUS WASTE SITES

This section presents information on landfills and lagoons, the two general types of sites used in this manual to demonstrate methods for estimating the potential for air emissions. For this manual, all types of uncontrolled solid waste sites, land disposal sites in particular, will be referred to as "landfills" and all types of uncontrolled liquid waste sites will be referred to as "lagoons." The estimation methods described for application to landfills and lagoons may generally be applied to solid and liquid hazardous waste, respectively.

This section addresses potential emission sources and potential air quality impacts. Discussion of potential air quality impacts covers the general types of air quality impacts by waste site category, and the basic transport mechanisms involved with the movement of contamination from lagoons and landfills. Where not otherwise specified, the general term hazardous waste site is used to refer to both landfills and lagoons that contain hazardous wastes and/or substances. Figures 2 and 3 depict these two types of sites in generalized schematic drawings.

The site and contaminant characteristics discussed below are general background information for working with the protocol presented in Section 3. The information provided will assist the site manager in developing conceptual models of landfills and lagoons. Based on this conceptual understanding, the site manager can then develop strategies for assessing the potential impacts and for estimating potential air emissions from these sites. The references cited in this section and those listed in the annotated bibliography contain further background material.

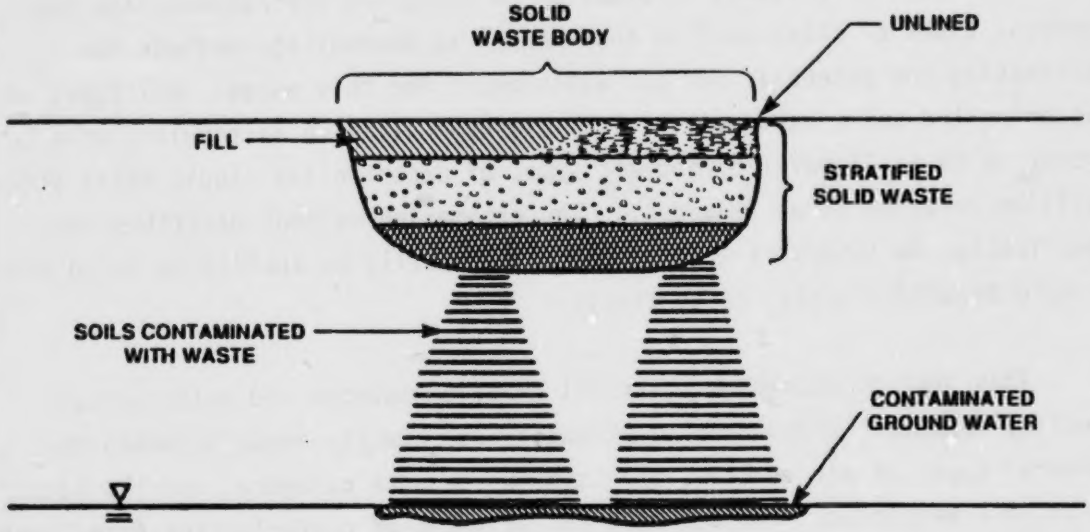
SOLID
WASTE BODY
UNLINED
FILL
STRATIFIED
SOLID WASTE
SOILS CONTAMINATED
WITH WASTE
CONTAMINATED
GROUND WATER

Figure 2. Conceptual schematic of a landfill.

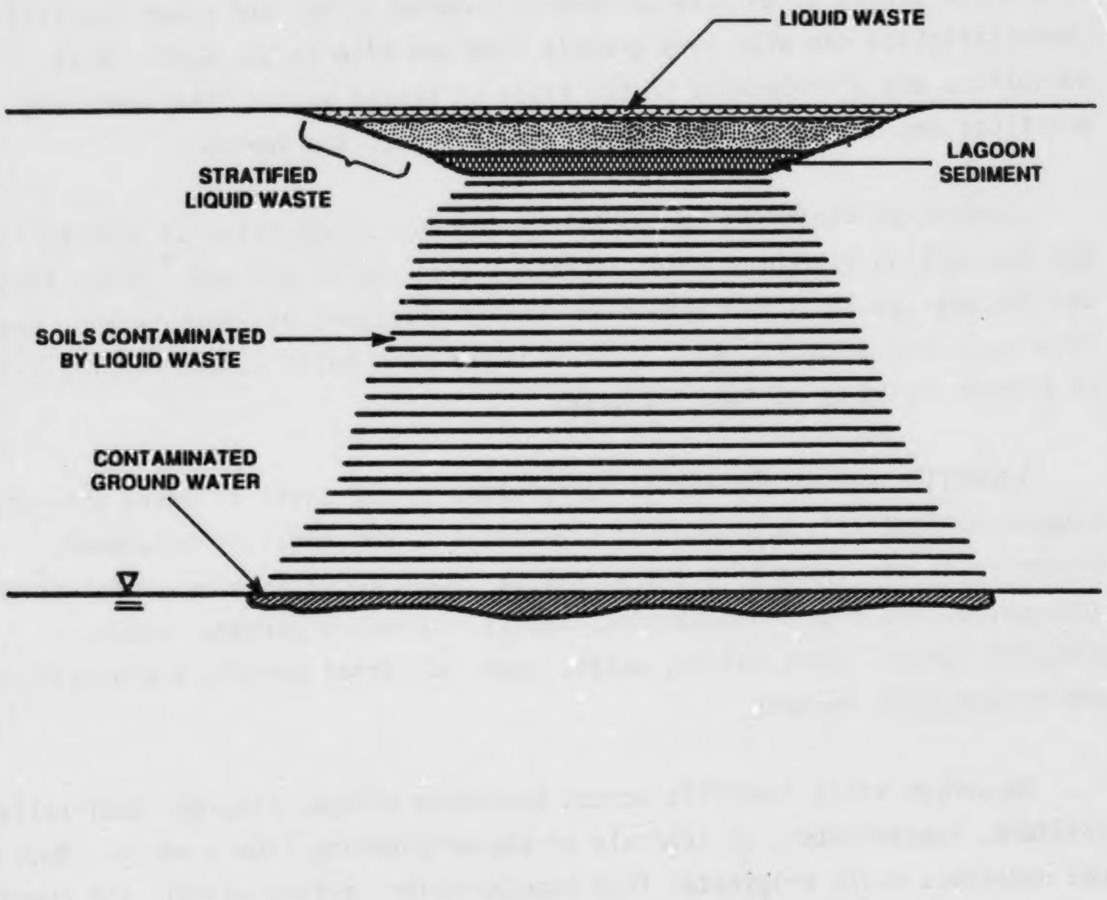
LIQUID WASTE
STRATIFIED LIQUID WASTE
LAGOON SEDIMENT
SOILS CONTAMINATED BY LIQUID WASTE
CONTAMINATED GROUND WATER

Figure 3. Conceptual schematic of a lagoon.

2.1 GENERAL DESCRIPTION

2.1.1 Landfills

Landfills are facilities into which wastes are placed for permanent disposal, and often are simply excavated pits. Landfills may vary in size from a few tenths of an acre to several hundred acres, and other landfill characteristics can also vary greatly from one site to the next. Most variations are attributable to the types of stored wastes, the operating practices and the age of the facility, and hence, its design.

Commercial landfills can be categorized by design criteria such as liners and gas-venting systems. Older landfills are usually unlined. Newer landfill designs may specify liner systems to retard transport of leachate and wastes into soils and ground water. Some landfills have built-in gas venting systems to prevent build up of landfill gases.

Landfills can be further differentiated by the types of waste they store. Commercial landfills are commonly classified as municipal or hazardous, depending on the types of waste accepted. Municipal landfills accept solid, semi-solid, and liquid nonhazardous wastes, including garbage, glass, plastics, paper, plant matter, ashes, some industrial wastes, and demolition and construction wastes.

Hazardous waste landfills accept hazardous sludge, liquids, semi-solids, residues, concentrates, or leachate or ash originating from a waste. Much of the hazardous waste originates from manufacturing, petrochemical, and chemical industries. Federal, state, and local regulations establishing minimum design standards and restricting types of acceptable landfill wastes have evolved over the last 25 years. In the past, mixtures of liquid and solid waste were common practice. Today, landfills can no longer accept liquid wastes or solids that contain free liquids unless they've been treated with fixatives and stabilizers to eliminate the free liquids prior to disposal.

Co-disposal landfills are sites that have received and mixed municipal and hazardous wastes. Any available disposal records may relate types of wastes and location/mixing within the landfill.

Most landfills that are selected as Superfund sites have undergone some form of closure. In some cases, currently operating facilities may have abandoned hazardous landfills at the same site. The appearance of a closed landfill will depend on when it was closed. Closure may mean that the site is covered with vegetation or that no waste is exposed. Telltale signals of covered waste are seeping leachate and odors. In the past, landfills were often sited in unpopulated areas close to the industry or industries generating the wastes, but population growth and development may result in people living or working in close proximity to the site.

Superfund sites may differ in significant ways from the types of commercial landfills discussed above. In some cases, the site history will be one of relatively indiscriminate disposal of hazardous substances. The sites may contain buried drums or pockets of dumped/spilled wastes that are not uniformly distributed across the disposal area. Information on waste types, disposal practices, date of disposal, etc. may be limited or non-existent. However, the protocol and measurement techniques presented in this manual are sufficiently generalized that they can be applied to such uncontrolled sites. Conversely, the emission models presented here may be of only limited use for sites where the chemical and physical parameters that serve as model inputs are poorly defined.

Potential Site Conditions--

The conditions encountered when investigating landfill sites will vary from site to site because of the differences in location, design, use, and operation. Figure 2 presents a conceptual schematic of a landfill site. The condition of the site cover material will vary greatly and is dependent, to a large extent, on the landfill's operational history. In the best situation, the landfill cover will extend over the entire land disposal area; the cover will have been constructed to minimize rainfall percolation into the waste body and regulated to minimize erosion of the cover. The degree to which the air, the surrounding native soils, and the ground water are protected from contamination from the wastes stored in the landfill will depend both on the landfill design and on the construction and operation of the waste storage facility. If the wastes have been disposed of in an unlined storage area, the likelihood of contamination of surrounding soils and eventual contamination of the ground-water beneath the landfill increases. If the landfill has been constructed at or below the ground-water table, the rate of transport of pollutants into the ground water further increases. Waste material in the landfill may be stratified by age of disposal and/or settling of the more dense waste.

Emission of air pollutants from landfills is dependent on the chemical and physical properties of the stored wastes and on the landfill design components which may have been implemented to reduce air emissions. Municipal landfills are sources of significant amounts of methane and carbon dioxide, and variable amounts of other non-methane hydrocarbons. Hazardous waste landfills often are sources of non-methane hydrocarbons, including volatile organic compounds (VOCs) and semi-volatiles, including pesticides. Co-disposal sites combine the emission potentials of both municipal and hazardous waste sites. The methane gases generated often can increase the migration potential of the high concentrations of non-methane hydrocarbons by acting as a carrier medium during bulk flow transport of these contaminants.

2.1.2 Lagoons

For purposes of this discussion, the term "lagoon" refers to the class of facility also known as surface impoundment or impoundment. This type of facility generally includes a natural topographic depression, a man-made excavation, or a diked area formed primarily of earthen materials. Lagoons are designed to hold liquid wastes or wastes containing free liquids. Lagoons include holding, storage, settling, and aeration ponds.

These waste sites may range in surface area from a few tenths of an acre to hundreds of acres. Man-made lagoons typically range in depth anywhere from 2 to 30 or more feet below land surface.

In some cases, for certain wastes, lagoons may be lined to minimize any fluid seepage. Clay, asphalt, soil sealant, and synthetic membranes are typical lining materials.

To prevent migration of pollutants into the native soils and ground water beneath the lagoon, lagoons are usually built above the naturally occurring water table and take advantage of any impermeable surface or subsurface soils. In areas with high ground-water tables, lagoons may be constructed on the land surface to minimize ground-water contact. Of course, use of liners and building above the water table will not prevent the release of contaminated air emissions from the surface of the lagoon, but these practices limit the possible routes of air emissions (see Section 2.2). Equally important are operating practices and the characteristics of wastes in the lagoon. The importance of these factors tends to parallel the landfill discussion above, as does the importance of lagoon siting practices.

Potential Site Conditions--

Actual site conditions that will be encountered when investigating lagoon sites will vary because of siting, lagoon design, lagoon usage, and differences in lagoon operations. Figure 3 presents a conceptual schematic of a lagoon site. The condition of the lagoon will depend, in large part, on the wastes stored there and the lagoon's operational history. Mixed wastes typically separate into stratified layers with the lighter materials near the surface and the denser liquids, sludges, and sediments having settled to the lagoon bottom. Contaminated soils around and beneath the lagoon are likely, as well as possible contamination of the underlying ground water.

2.1.3 Equivalent Units

Sites containing mixed wastes or having other types of inherent variability may require separate remedial options to be considered for each equivalent area. During the remedial investigation, the site should be theoretically divided into equivalent units for estimating baseline emissions and evaluating potential emissions during remediation. For example, a site containing an abandoned landfill, sludge pits, and buried drums would have at least three distinct units and maybe more. If the type, concentration, or distribution of a given form of contamination varies, then further subdivision of the units should be considered. Similarly, if the soil media or proximity of receptors varies significantly across the site, then further subdivision of the units may be warranted.

2.2 ROUTES OF EXPOSURE

Waste site characterizations performed during a remedial investigation are intended to determine potential or existing contaminant migration by the direct contact, surface water, ground water, and air pathways. Each pathway represents a potential route of exposure to the public and the general environment. Figures 4 and 5 show the potential routes for contaminant migration from landfills and lagoons, respectively. The focus of this manual is the air pathway, and several routes exist for contaminant emissions within this one pathway.

Organic and inorganic emissions from surface wastes may occur as gases, aerosols, and contaminated particulate matter. Where gas migration controls, (e.g., gas venting systems) have been installed, volatile emissions from the controls are likely to be higher than emissions from the site surface. The lateral migration of solid and liquid wastes into the surrounding soils and beneath the containment area can create large areas of contaminated subsurface soils. The contaminated soils also represent a source of potential air emissions via the transfer of contaminants into the air-filled spaces in the soil matrix. The contaminated soil gas can then transfer contaminants into the atmosphere at the surface soil/atmosphere interface.

The generation of leachate from landfills and lagoons can accelerate the pollutant migration into the ground water below and provide an additional source of air emissions resulting from the volatilization of dissolved contaminants in the ground water. The contaminated groundwater also can transfer contaminants into the soil gas and hence the atmosphere.

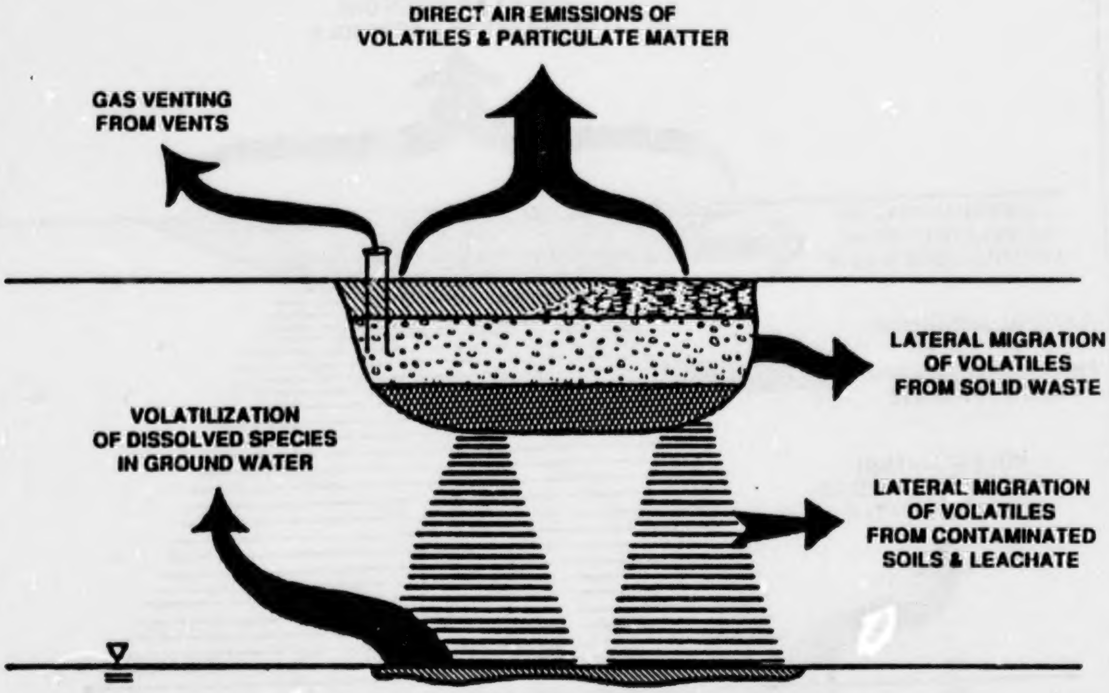
DIRECT AIR EMISSIONS OF VOLATILES & PARTICULATE MATTER
GAS VENTING FROM VENTS
LATERAL MIGRATION OF VOLATILES FROM SOLID WASTE
VOLATILIZATION OF DISSOLVED SPECIES IN GROUND WATER
LATERAL MIGRATION OF VOLATILES FROM CONTAMINATED SOILS & LEACHATE

Figure 4. Conceptual Schematic Showing Air Contaminant Pathways From an Unlined Landfill.

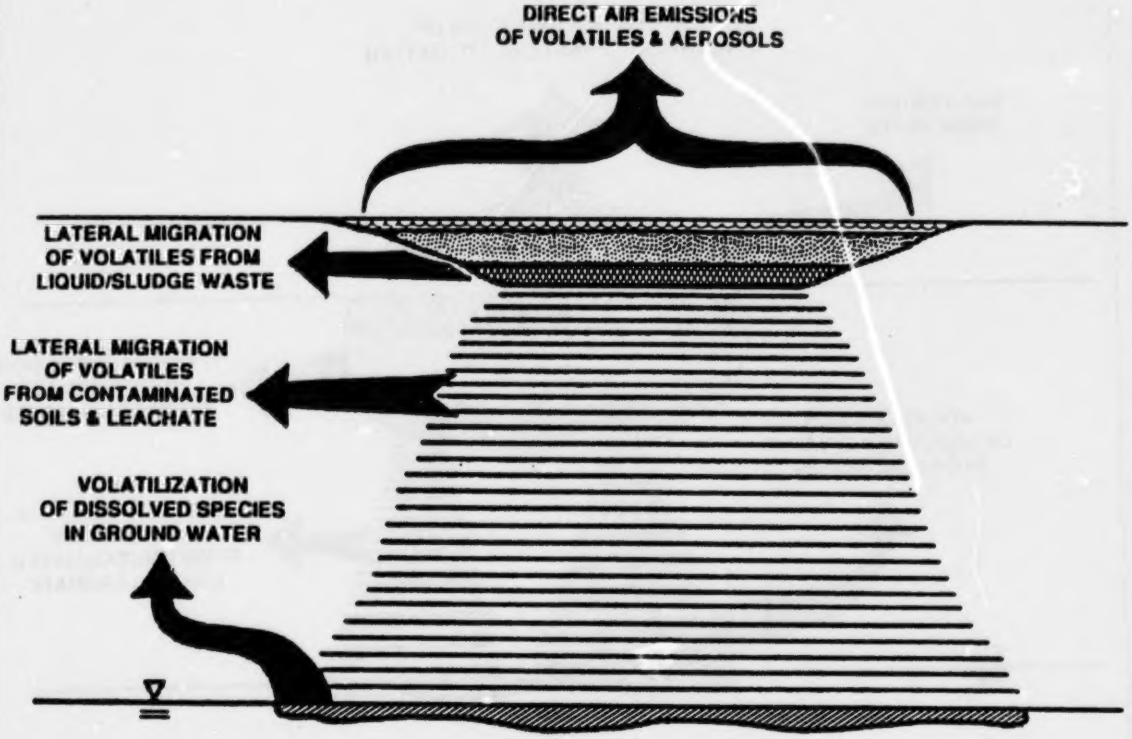
DIRECT AIR EMISSIONS
OF VOLATILES & AEROSOLS
LATERAL MIGRATION
OF VOLATILES FROM
LIQUID/SLUDGE WASTE
LATERAL MIGRATION
OF VOLATILES
FROM CONTAMINATED
SOILS & LEACHATE
VOLATILIZATION
OF DISSOLVED SPECIES
IN GROUND WATER

Figure 5. Conceptual Schematic Showing Air Contaminant Migration From an Unlined Lagoon with No Cover.

2.2.1 Key Parameters and Critical Factors Affecting Emissions from Landfills

The generation of landfill emissions depends on several key chemical and physical properties of the waste materials stored at these sites along with site and meteorological factors. Table 1 presents these key factors along with the qualitative effects these factors may have on baseline emissions. These qualitative effects can be used to help estimate the potential air emissions from the site, given critical factors imposed by the site. A discussion of each parameter is outside the scope of this document, but in general, for volatile compounds the rate limiting step is the movement of vapors through the soil. Volatilization into the soil pore spaces is usually quite rapid as is the transfer from the soil-gas into the atmosphere once the soil/air interface has been reached.

Additional information about the key physical and chemical properties of the waste material are presented in Appendix B. Users should consult the references cited below and those listed in the annotated bibliography (Appendix A) for additional background material. General reading materials that may prove helpful include: Guidance Document for Cleanup of Surface Impoundment Sites,(4) Model Prediction of Volatile Emissions,(5) Air Pollution Assessment of Toxic Emissions from Hazardous Waste Lagoons and Landfills,(6) Air Quality Assessment for Land Disposal of Industrial Wastes,(7) Estimating Air Emissions from Disposal Sites,(8) and Air Pollution Problems of Uncontrolled Hazardous Waste Sites.(9)

2.2.2 Key Parameters Affecting Emissions from Lagoons

Figure 5 presents a generalized schematic of the volatilization process from lagoons. In general, the process consists of two steps: vaporization from the surface liquid layer into the boundary air layer and then mass transfer from the boundary layer to the bulk atmosphere. The rate of vaporization is dependent on factors such as the compound's concentration, Henry's Law constant, water solubility and the system temperature. Mass transfer into the bulk atmosphere is dependent on compound properties such as molecular weight and diffusion coefficient, and site-related factors such as

TABLE 1. IMPORTANT PARAMETERS IN DETERMINING AIR EMISSIONS AND THEIR QUALITATIVE EFFECTS ON BASELINE EMISSION ESTIMATES (BEEs)

Parameter	Qualitative Effect on BEEs[a] Volatiles	 Particulate Matter
Site Conditions		
Size of Landfill or Lagoon	Effects overall magnitude of emissions but not rate per area.	Effects overall magnitude of emissions, but not rate per area.
Amount of Exposed Waste	High	High
Depth of Cover on Landfills	Medium	High
Presence of Oil Layer	High	High
Compaction of Cover on Landfills	Medium	Low
Aeration of Lagoons	High	High
Ground Cover	Medium	High -
Weather Conditions		
Wind Speed	Medium	High
Temperature	Medium	Low
Relative Humidity	Low	Low
Barometric Pressure	Medium	Low
Precipitation	High	High
Solar Radiation	Low	Low
Soil/Waste Characteristics		
Physical Properties of Waste	High	High
Adsorption/Absorption Properties of Soil	Medium	Low
Soil Moisture Content	High	High
Volatile Fraction of Waste	High	Low
Semi-Volatile/Non-Volatile Fraction of Waste	Low	High
Organic Content of Soil and Microbial Activity	High	Low

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[a] High, medium, and low in this table refer to the qualitative effect that the listed parameter typically has on baseline emissions.

temperature, pressure, and wind speed. Berms, wind breaks, and lagoon geometry affect the wind speed at the liquid surface and can thereby control the rate of mass transfer. In general, volatility increases as the molecular weight of the compounds present decreases.

2.3 MAGNITUDE OF AIR EMISSIONS

The magnitude of baseline air emissions from landfills and lagoons is dependent on waste-specific chemical and physical factors and site-specific environmental factors. Limited data are available on measured air emission fluxes (rate per area) from previously studied waste sites (Table 2). These data can be used to give the site manager some idea of typical baseline emission estimation (BEEs) and a limited comparison of BEEs for different types of waste sites. Emission flux data for disturbed or exposed wastes are included to demonstrate the potential for increased emissions of volatiles during waste remediation.

2.4 EMISSIONS OF POTENTIAL INTEREST AT NPL SITES

The types of emissions at a hazardous waste site are dependent on the types of waste present, and these in turn are dependent on the types of industries and manufacturers that produced the waste. A listing of the typical wastes generated by 30 various industries and manufacturers can be found in the Handbook of Industrial Waste in California (11). The 25 most frequently detected compounds at 546 hazardous waste sites are summarized in

TABLE 2. SUMMARY OF AVERAGE BASELINE EMISSIONS FOR VARIOUS EMISSION SOURCES

Waste Type	Source Type	Baseline Emission Estimate For TNMHC[a] (ug/m^2-min)	Disturbed or Exposed Waste Emissions For TNMHC (ug/m^2-min)
NPL/Hazardous Waste Sites	Landfills		
	Site A	360	190,000
	Site B	740	26,000
	Site C	29	170,000
	Lagoons		
	Site D	43	640,000
Industrial Waste	TSDF[c] Facilities		
	Active Landfills		
	Site E	---	44-150
	Site F	---	47
	Site G	---	9
	Inactive Landfills		
	Site H (covered)	<1.2	---
	Site I (covered)	<1.2	---
	Land Treatments		
	Site J	---	610-9600
	Lagoons		
	Site K	120	---
	Site L	570	---
	Site M	9-31[b]	---
	Site N	630	---

[a] TNMHC = Total Non-Methane Hydrocarbons.
[b] Different assessment techniques were used.
[c] Transfer, storage, and disposal facilities (RCRA)

Source: Reference 10.

Table 3 according to the type of media, i.e., groundwater, surface water, or air. The table shows the number of sites where each contaminant was detected and the contaminant's relative rank for each type of media. Another useful listing for selecting contaminants with the potential for emissions of concern, is the list of toxic compounds most commonly addressed by state and local regulatory agencies given as Table 4.

2.5 SUMMARY OF POTENTIAL RECEPTORS

Receptors can be divided into three broad categories:

- On-site workers;
- Off-site populace; and
- Non-human receptors.

The on-site workers are in the closest proximity to the hazardous waste site and are potentially subject to the most acute exposure to hazardous substances. The use of personal protective equipment, real-time field instruments, personnel monitoring, site controls, and designated work zones are designed to ensure that field personnel are properly protected against the hazards present at the work site.

The off-site (and any on-site) population in close proximity to the hazardous waste site is another receptor of primary concern. These people are often acutely aware of the hazardous waste site and the potential for contaminant exposure. Section 3 provides an approach for estimating emissions which can subsequently be used to predict the airborne contaminant concentration for downwind receptors to assist in the establishment of appropriate action levels. Use of this protocol, coupled with an effective monitoring and modeling program, will provide useful information for the site's community relations program.

TABLE 3. MOST FREQUENTLY REPORTED SUBSTANCES AT 546 NATIONAL PRIORITY LIST SITES

Substance Identified at Hazardous Waste Disposal Sites	Sites[a]	Air	Ground Water	Surface Water
		Number of Sites (Rank)[bc]	Number of Sites (Rank)[b]	Number of Sites (Rank)[b]
Most Frequently Occurring				
1. Trichloroethylene	179	8 (5)	127 (1)	49 (3)
2. Lead	162	7 (6)	77 (4)	84 (1)
3. Toluene	153	1 (3)	81 (3)	40 (4)
4. Benzene	143	1 (2)	84 (2)	36 (5)
5. Polychlorinated Biphenlys (PCBs)	121	6 (4)	29 (21)	54 (2)
6. Chloroform	111	1	70 (6)	24 (11)
7. Tetrachloroethylene	90	3 (16)	57 (7)	17 (14)
8. Phenol	84	3 (16)	43 (9)	28 (8)
9. Arsenic	84	2 (17)	45 (8)	35 (6)
10. Cadmium	82	31 (17)	28 (16)	28 (9)
11. Chromium	80	1	34 (14)	33 (7)
12. 1,1,1-Trichloroethane	79	3 (18)	58 (6)	20 (12)
13. Zinc and Compounds	74	2	28 (17)	27 (10)
14. Ethylebenzene	73	7 (7)	36 (12)	14 (20)
15. Xylene	71	9 (4)	32 (15)	8 (25)
16. Methylene Chloride	63	2	36 (13)	17 (15)
17. Trans-1,2-Dichloroethylene	59	1	42 (10)	17 (16)
18. Mercury	54	4 (10)	27 (20)	20 (13)
19. Copper and Compounds	47	6	17 (24)	16 (18)
20. Cyanides (Soluble Salts)	46	2	16 (25)	16 (19)
21. Vinyl Chloride	44	4 (11)	28 (18)	10 (23)
22. 1,2-Dichloroethane	44	2	25 (21)	17 (17)
23. Chlorobenzene	42	0	23 (23)	9 (23)
24. 1,1-Dichloroethane	42	0	28 (19)	8 (24)
25. Carbon Tetrachloride	40	2	25 (22)	12 (21)

[a] Number of sites at which substance is present. Substances may be present in one, two, or all three environmental media at all sites at which it is known to be rpesent. Therefore, the number of sites at which each substance is detected in environmental media may not equal the number in this column.

[b] Not all ranks will be represented in all media because not all chemicals found in media are among those found most frequently at site.

[c] Volatile organics not otherwise specified were reported as being detected most often (rank 1) in the air medium.

Source: Reference 12

TABLE 4. TOXIC POLLUTANTS MOST COMMONLY ADDRESSED BY STATE AND LOCAL AGENCIES

Acetaldehyde
Acrolein
Acrylonitrile
Allyl Chloride
Arsenic
Asbestos
Benzene
Benzidine
Benzo(a)pyrene
Benzyl Chloride
Beryllium
Bis(chloromethyl)ether
1,3-Butadiene
Cadmium
Carbon Tetrachloride
Chlordane
Chlorobenzene
Chloroform
Chloroprene
Chromium
Cresol
1,4-Dichlorobenzene
3,3-Dichlorobenzidine
Dimethyl Sulfate
1,3-Dioxane
Dioxins
Epichlorohydrin
Ethylene Dibromide
Ethylene Dichloride
Ethylene Oxide
Ethylenimine (azridine)
Formaldehyde
Heptachlor
Hexachlorocylopentadiene
Hydrazine
Hydrogen Sulfide
Lead
Lindane
Maleic Anhydride
Manganese
Mercury
Methyl Bromide
Methyl Chloride
Methyl Chloroform
Methylene Chloride
beta-Naphthylamine
Nickel
Nitrobenzene
n-Nitrosodimethylamine
Nitrosomorpholine
Parathion
Perchloroethylene
Phenol and Chlorinated Phenols
Phosgene
Polychorinated Biphenyls (PCBs)
Polycyclic Aromatic Hydrocarbons (PAH)
Propylene Oxide
Radionuclides
Styrene
1,1,2,2-Tetrachlorethane
Tetrahydrofuran
1,1,2-Trichloroethane (vinyl trichloride)
Toluene
Trichoroethylene
Vinyl Chloride
Vinylidene Chloride
Xylene

Source: Reference 12.

Non-human receptors also may be a concern at some hazardous waste sites. Disturbance of the site may lead to exposure through inhalation of contaminated air or exposure through ingestion of or direct contact with contaminants deposited on plant and inert surface. The possibility of inhalation exposure may affect feral or domesticated animals downwind of the site. This also impacts humans in that animal exposure to pollutants can lead to contamination accumulation in the food chain.

Certain gaseous pollutants (e.g., ozone, oxides of sulfur and nitrogen), if present in high concentrations, also can affect plant and animal growth. Deposition of airborne contaminants may cause stressed vegetation, release pesticides and herbicides, or impact the value/usability of agricultural crops. Also, deposition of metals or other pollutants in surface waters may impact marine life. Copper and some other metals can cause fish kills at very low concentrations.

SECTION 3
PROTOCOL FOR BASELINE EMISSION ESTIMATES

This section presents a protocol for developing baseline emission estimates (BEEs). This protocol is a component of an air pathway analyses (APA) program to assess potential air quality impacts from hazardous waste sites. While not all sites will require BEEs, the first three steps in the protocol should be implemented to see if BEEs are necessary for a given site. The protocol is a recommended guideline; the level of effort that is required or the need to develop BEEs for individual sites must be determined on a case-by-case basis.

3.1 PROTOCOL STEPS FOR DEVELOPING BEEs

Figure 6 diagrams a protocol for developing BEEs. The protocol was developed to help the site manager to determine baseline emission rates and absolute levels of emissions. These values can be used as inputs to dispersion models to assess the air impacts for receptor locations of interest. The activities identified in this flow chart are consistent with the steps of the CERCLA remedial investigation process that involve the assessment of the air contaminant migration pathway. Although the protocol was developed for NPL sites, it also applies to assessing air emissions from other hazardous waste sites. The flow chart is applicable to all sites, regardless of the type of site (landfill, lagoon, waste pile, etc.), type of waste, or the potential for the site to generate air emissions. Each step of the protocol is described below.

3.1.1 Define the APA Objective

CERCLA and SARA legislation highlight the basic objectives for all remedial investigations. Simply stated, these objectives are to provide data that are "necessary and sufficient" to characterize the "nature and extent" of contamination on site. In addition, they mandate that "all potential

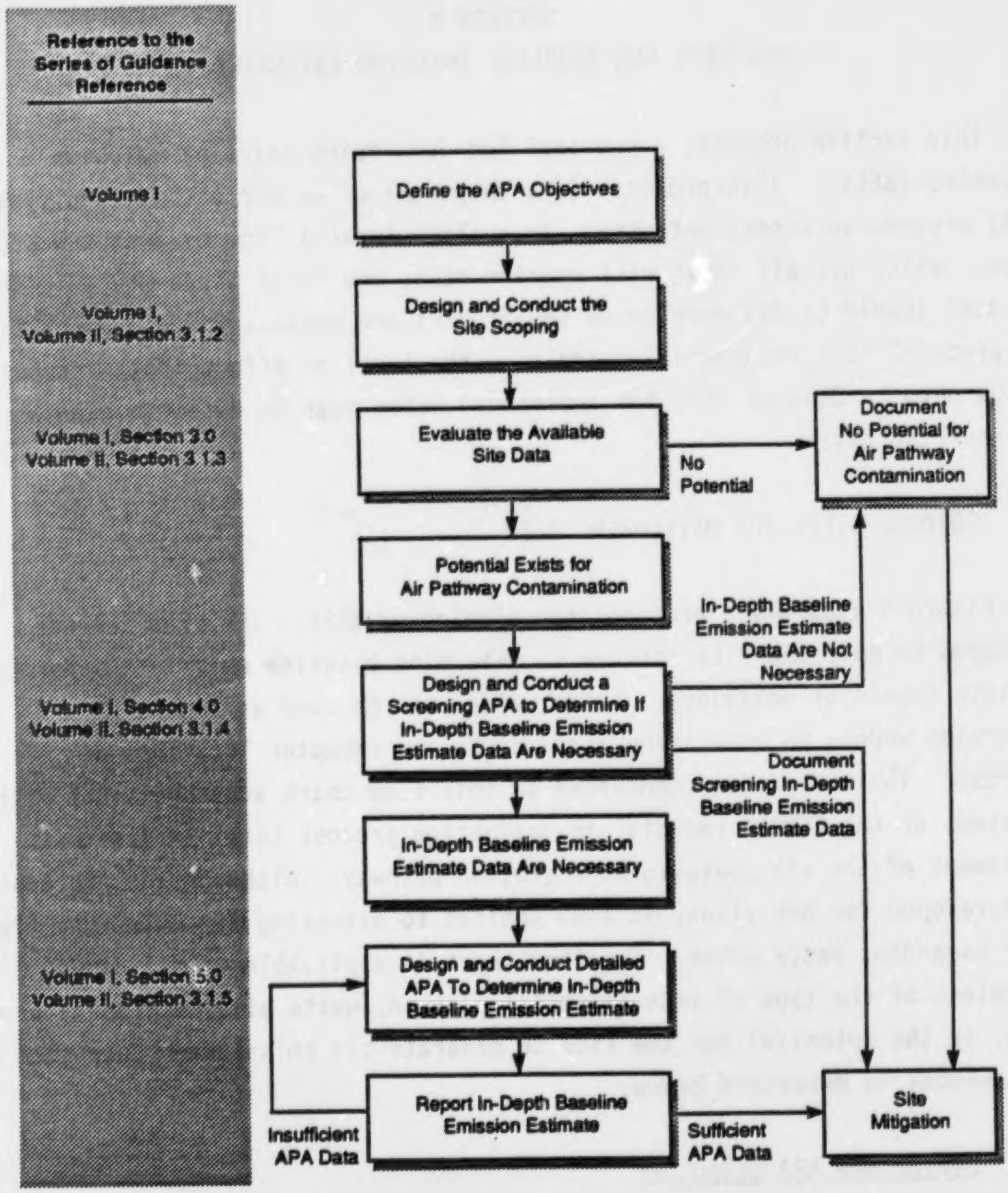

Reference to the Series of Guidance Reference
Volume I
Volume I, Volume II, Section 3.1.2
Volume I, Section 3.0 Volume II, Section 3.1.3
Volume I, Section 4.0 Volume II, Section 3.1.4
Volume I, Section 5.0 Volume II, Section 3.1.5
Define the APA Objectives
Design and Conduct the Site Scoping
Evaluate the Available Site Data
No Potential
Document No Potential for Air Pathway Contamination
Potential Exists for Air Pathway Contamination
In-Depth Baseline Emission Estimate Data Are Not Necessary
Design and Conduct a Screening APA to Determine If In-Depth Baseline Emission Estimate Data Are Necessary
Document Screening In-Depth Baseline Emission Estimate Data
In-Depth Baseline Emission Estimate Data Are Necessary
Design and Conduct Detailed APA To Determine In-Depth Baseline Emission Estimate
Report In-Depth Baseline Emission Estimate
Insufficient APA Data
Sufficient APA Data
Site Mitigation

Figure 6. Flowchart of activities for developing screening and in-depth baseline emission estimates.

migration pathways for contaminations" require characterization. As the first step of the protocol to assess baseline emissions, site-specific objectives should be developed; this will generally occur simultaneously with the performance of Steps 2 and 3 (data collection and review) of the protocol. The site manager should consider the following issues when formulating site-specific objectives:

- What information is already available? As described in Section 3.1.2, available information should first be reviewed before developing final site-specific objectives. This preliminary review of information will provide necessary background information and aid in identifying data gaps.

- What pathways must be considered? Except in rare cases, all pathways, namely air, soil, and water, must be considered.

- What is technically possible? Site and situational factors that may adversely affect the air pathway investigation should be identified to avoid establishing unrealistic objectives. These factors can range from complexity in site geology/hydrogeology and complex terrain to the feasibility of detecting the contaminants of interest.

- What time deadlines exist? Schedule constraints can affect the nature of the investigation and must be balanced with technical concerns.

- What data quality objectives are required? Data must be of a known accuracy and precision for use in evaluating the air pathway.

- What program is most cost effective? The type, level, and extent of contamination per migration pathway will primarily determine how the available resources are apportioned. It is also necessary to collect, integrate, and consider a variety of types of data, including technical information, institutional issues, political issues, public protection, community relations issues, and community concerns.

- What contaminants must be considered? The investigation will typically involve identifying and characterizing the extent of the contamination. Concentrations of individual or summed indicator compounds are often selected to represent the extent of total contamination. Site-specific objectives should neither identify specific indicator compounds nor require characterization of all compounds.

Table 5 provides examples of objectives related to baseline emissions estimates. The first step in developing site-specific APA objectives is to collect and review readily available site historical records. The potential for air emissions can be inferred from the review of preliminary site information. While baseline emissions may be low, during remediation sites have the potential for air emissions of particulate matter (semi-volatile organics, metals, and other inorganic contaminants) and enhanced volatile organic emissions.

Among the types of information that can be reviewed and used to develop site-specific APA objectives are: waste characteristics; distribution of the waste; orientation of the general public to the emission source concerns; technical feasibility; and program resources. The first three items are discussed below.

- Waste Characteristics. Knowledge of the industrial process or the waste source involved can suggest the types of chemicals or agents that may be in the waste. For example, volatile emissions are likely from waste sites with organic solvents or petroleum waste. Wastes in liquid form tend to have higher baseline emissions than wastes in solid form. In addition, identifying common decomposition products of the chemicals identified in the waste may be useful. It is helpful to categorize potential air contaminants by their generic volatility: volatiles, semi-volatiles, and non-volatiles.

TABLE 5. EXAMPLES OF APA OBJECTIVES FOR BEEs

- Characterize the air emissions potential for volatile species and particulate matter from the undisturbed site.
- Characterize the air emissions potential for volatile species and particulate matter from the disturbed site.
- Identify contaminants of concern.
- Provide baseline emission estimates that can be used to assess the health risk and the need to mitigate.
- Provide baseline emission estimates that can be used to assess the need for on-site or fenceline ambient monitoring.

Examples of the types of compounds in each category are listed in Table 6. The categories group together compounds with similar physical behavior in the atmosphere and thus are useful for predicting emissions potential.

- Distribution of the Waste. The relative position of the waste can influence the potential for air emissions and, thus, the APA objectives. The amount and nature of overburden strongly influences the baseline emissions at a site. Semi-volatiles and non-volatiles present near the surface can be emitted as windblown particulate matter. Waste piles may have relatively high emissions of both volatile organics and particulate matter due to their geometry and surface area to volume ratio.

- Location of the Affected Population and Community Concerns. The population potentially at risk from exposure to toxic air emissions from the site must be identified and the exposure characterized. The close proximity of residential areas may require the addition of measurement and monitoring activities for health and safety purposes that are beyond what is necessary to develop BEEs for the site. Thus, the site-specific objectives may include a component related to determining the potential impact on the nearest population (e.g., air monitoring at the site boundary).

The APA objectives should be documented and circulated for peer review by staff members that have knowledge of the site, APA, and the site mitigation process. The review process may also help identify site characterization data needs. Developing site-specific objectives is an iterative process; more than one round of data gathering, review, and discussion may be needed to develop satisfactory objectives.

TABLE 6. POTENTIAL AIR CONTAMINANTS BY GENERIC TYPE OF CONTAMINANT

Volatiles (>1 mm mercury vapor pressure at 25°C)

- All monochlorinated solvents; also trichloroethylene, trichloroethane, tetrachloroethane
- Most simple aromatic solvents: e.g. benzene, xylene, toluene, and ethylbenzene
- Most alkanes up to decane (C_{10})
- Inorganic gases: e.g. hydrogen sulfide, chlorine, and sulfur dioxide

Semivolatiles (1-10^{-7} mm mercury vapor pressure at 25°C)

- Most polychlorinated biphenyls, dichlorobenzenes, aniline, nitroaniline, and phthalates
- Most pesticides: e.g. dieldrin, toxaphene, and parathion
- Most complex alkanes: dodecane and octadecane
- Most polynuclear aromatic's: e.g. napthalene, phenanthrene, and benz(a)anthrencene
- Mercury

Non Volatiles or Particulate Matter ($<10^{-7}$ mm mercury vapor pressure at 25°C)

- Larger polynuclear aromatics: e.g. chrysene
- Metals: e.g. lead and chromium
- Other inorganics: e.g. asbestos, arsenic, and cyanides

3.1.2 Site Scoping

The second step in the development of BEEs is collection of available information about the site. This should be a quick, straightforward information search, involving the collection of records, reports, shipping manifests, newspaper clippings, and information from interviews with people living close to or affiliated with the site. For NPL sites, data should be available from the preliminary assessment and site inspection conducted prior to inclusion on the NPL. The type of information to be collected parallels, for the most part, the factors considered in creating the objective. These include:

- Source of the waste (type of industry);
- Composition of the waste (organic-volatile/semi-organic; inorganic-metals, others; biological; radioactive);
- Distribution of the waste and cover material limiting volatilization and uptake of particulate matter from the waste;
- Distance from the waste to the property fenceline; and
- Representative meteorological data.

3.1.3 Evaluate Available Site Data

The existing site information (including the site inspection report) should be evaluated to determine the potential for release of air emissions. Examples of types of contaminants and situations to be evaluated are provided in Table 7. If it is determined through this assessment that the site poses no significant potential for air pathway contaminant emissions, then no further evaluation of the baseline emissions is required. The site manager must record the basis for this decision and include these data in the site investigation documentation. In most cases, insufficient information will be available at this stage, and further work

TABLE 7. EXAMPLES OF TYPES OF CONTAMINANTS AND SITUATIONS THAT MAY INDICATE A POTENTIAL FOR AIR PATHWAY CONTAMINATION

Situation/Condition	Volatiles	Particulate Matter	Comment
• Site Odors, Neighborhood Complaints	✓		Indicates moderate to high levels of BEEs.
• Observation of Dust Clouds During Wind		✓	Check soil cover and look for waste piles.
• Evidence of Metal Corrosion	✓	✓	Look for corrosive agents.
• Vent pipes	✓		Check records to determine if the site is a codisposal facility.
• Seeps of Waste	✓		Probable buried wastes.
• Weathered Waste Surface	✓		Emissions of disturbed waste may be very high.
• Aged and Layered Waste	✓		Likely that volatiles are higher in underlying lay chemicals possible.
• Aerated Lagoons	✓	✓	Increased emissions.
• Exposed Waste	✓	✓	Increased emissions.
• Industrial Wastes	✓		Waste mixtures likely, check for particular solvent types, aromatic and halogenated organic solvents.
• Petroleum Wastes	✓		Tar/wastes with volatile emissions likely.
• Industrial Wastes/ Paint Wastes	✓		Organic volatiles likely.

(Continued)

TABLE 7. (Continued)

Situation/Condition	Volatiles	Particulate Matter	Comment
• Recycling or Plating Wastes		✓	Metal-containing particulate matter likely.
• Municipal Wastes	✓		Methane/carbon dioxide volatiles likely; look for industrial waste.
• Hospital Wastes	✓	✓	Solvent used likely; biological hazards and radioactive waste possible.
• Chemical Production or Storage	✓	✓	High concentrations of specific chemicals likely.
• Site Inspection	✓		Gas detection results indicate the presence of gas species and the potential for emissions.
		✓	Visual inspection and particle counting/detection results indicate the potential for particulate matter emissions.

will be warranted. If air emissions are a potential concern, the next step of the protocol (site screening study) should be implemented to provide additional information to make a judgement regarding the potential for air emissions from the site. At this point the site-specific APA objectives should be reviewed by the site RPM to ensure they are still realistic, attainable, and applicable.

3.1.4 Design and Conduct the Site Screening Study

Designing a site screening study to assess the air emissions potential involves the selection of an air emissions measurement/assessment method. The four broad categories of measurement/assessment approaches include:

- Direct emissions measurement;
- Indirect emissions measurement;
- Air monitoring/modeling; and
- Emissions (predictive) modeling.

Each approach includes a range of possible methods that can.be categorized according to their level of complexity as screening (quick and simple) methods or in-depth (very detailed) methods.

The activities necessary to design and conduct the site screening study are:

- Determine the feasibility of obtaining the screening data. (Identify any site factors that may limit this activity.)

- Select appropriate tracer species, screening methods, and applicable equipment/instrumentation.

- Design the site inspection technical approach and test plan, including the Quality Assurance/Quality Control Program. Make sure that all units of a combined site are studied.

- Circulate the site screening approach for review and ensure the screening addresses the site-specific objective(s).
- Modify the site screening program, as necessary.
- Conduct the site screening study and document the findings.
- Determine if the site screening study was adequate to characterize the air contamination migration pathway and if detailed BEE data are necessary. If detailed BEEs are necessary, initiate the in-depth site characterization study. If not, document the site inspection survey results and the basis for discontinuing the APA.

One preliminary step is to evaluate those key factors that affect the air emissions of volatiles and particulate matter. The factors were presented in Section 2 and are summarized in the check-list presented in Figure 7. This figure can be used to summarize site information and facilitate the decisions regarding selecting and implementing screening methods. If the site contains a waste type that has the potential to create air emissions, the most important factors which determine the baseline emissions are typically site conditions and weather conditions. Once the checklist (Figure 7) has been completed and some knowledge of the factors affecting air emission processes is gained, the site manager must select appropriate indicator species and select air emission screening methods, equipment, and instrumentation.

Indicator species are species found in the waste that can be used to represent a group of species in determining emissions. If little is known about which specific species are present at the site, select an indicator that represents a family or class of species so that gross data on emissions can be obtained and then later refined. Table 8 provides information that will aid in this selection process. All highly toxic compounds likely to be present at the site should be on the target compound list, along with the indicator species. The ideal indicator species or class of species is:

Parameter	General Effect		Site Information	Effect on Emissions			
	Volatile	PM		Volatiles		Particulate Matter	
				Increase	Decrease	Increase	Decrease
SITE CONDITIONS							
Amount of Exposed Waste	High	High					
Depth of Soil	Medium	High					
Presence of Oil Layer	High	High					
Compaction of Cover	Medium	Low					
Aeration of Lagoons	High	High					
Ground Cover	Medium	High					
WEATHER CONDITIONS							
Wind Speed	Medium	High					
Temperature	Medium	Low					
Relative Humidity	Low	Low					
Barometric Pressure	Medium	Low					
Precipitation	High	High					
Solar Radiation	Low	Low					
SOIL/WASTE CHARACTERISTICS							
Physical Properties	High	High					
Sorption of Soil	Med	Low					
Soil Moisture	High	High					
Volatile Fraction	High	Low					
Semi/Non-Volatile Fraction	Low	High					
Organic Content of Soil	High	Low					

Figure 7. Checklist of factors affecting air emissions per unit. The site manager should use this to summarize site data on critical factors to determine how these factors may affect the air emissions potential.

TABLE 8. FACTORS TO CONSIDER IN SELECTING AN INDICATOR SPECIES FOR STUDY

1) Homogeneity of waste and representativeness of proposed indicator species;
2) Variety of types of air contaminants (organic, inorganic, biohazard, radioactive);
3) Physical state of air contaminants (gas, liquid, solid);
4) Level of air contaminant emission;
5) APA objectives;
6) Feasibility of air monitoring for proposed indicator species;
7) Availability of standard sampling/analytical/monitoring techniques;
8) Potential interferences for the proposed indicator species; and
9) Health effects.

- Present in the air emissions in a fixed ratio;
- A non-reactive or stable species;
- Present at levels above analytical detection limits;
- Unique to the site (not in background air samples);
- Representative of the "worst case" toxicity for compounds at the site; and
- Applicable for existing measurement and monitoring technologies; and
- Of known toxicity and exposure criteria.

A list of candidate indicator species can be developed from those species previously identified in analysis of the waste or by identifying broad-band type indicators that represent the type of waste identified in the scoping. Candidate species should match as closely as possible the characteristics of an ideal indicator species. The two main required characteristics are presence in the air emissions from the site and the ability to measure/monitor the species using commercially available methods and instruments. Examples of broad-band, class and indicator species are given in Table 9.

In addition to selecting indicator species, the site manager must select the most suitable air emissions sampling methods for screening. Screening methods are summarized in Table 10. Air emissions measurement/assessment methods are described in detail in Section 4. The four general approaches for screening emissions are described below.

TABLE 9. EXAMPLES OF BROAD-BAND, CLASS, AND INDICATOR SPECIES

BROAD BAND	CLASSES OF COMPOUNDS	INDICATOR SPECIES
Volatile Organics	Aliphatics	Alkanes, Total Hydrocarbons as Pentane
	Aromatics	Benzene, Xylene, Toluene
	Halogenated Species	Trichloroethene, Trichloroethane, Vinyl Chloride
	Oxygenated Species	Ethanol, Formaldehyde
	Sulfur Containing Species	Mercaptans, Thiophenes
	Nitrogen Containing Species	Benzonitrile
Volatile Inorganics	Acid Gases	Sulfur Dioxide, Hydrogen Chloride
	Sulfur Containing	Hydrogen Sulfide
Semi-Volatile Organics	Polynuclear Aromatics (PAH)	Napathalene, Benzo-(a)Pyrene
	Polychlorinated Biphenols (PCBs)	PCBs As Aroclor 1254
Non-Volatiles	Metals	Lead, Chromium, Zinc

TABLE 10. TYPES OF SCREENING METHODS FOR ESTIMATING EMISSIONS*

- Direct Emissions Measurement
  - Head Space Sampler
  - Head Space Analysis of Bottled Sample
- Indirect Emissions Measurement
  - Upwind/Downwind
  - Mass Balance
  - Real-time Instrument Survey
- Air Monitoring/Modeling
  - Upwind/Downwind
- Emissions (Predictive) Modeling
  - Superfind Exposure Assessment Manual (SEAM) models
  - Any model using literature values and assumed concentrations

*See Section 4 for more detail.

- Direct Emissions Measurement. Concentration measurements can be made of the air directly above the waste, either the "head space" or air space of a sampler placed on the waste, or the head space of a sample bottle half-filled with waste material. The screening provides a relative measure of the emission potential of various wastes/locations. High concentrations of volatile species in the head space can indicate high potential for air emissions from the site. Likewise, low concentrations can indicate low potential for air emissions. The advantage of these screening methods is that they are relatively quick, easy and inexpensive to perform. They also can have the highest sensitivity (i.e., detect the contaminants even at low concentrations), since they measure concentrations at the source. The techniques are only applicable to volatile gas species. These data can be used to estimate emission factors to indicate the potential for air emissions.

- Indirect Emissions Measurement. These types of sampling methods can be used for any type of contaminant such as volatiles and/or particulate matter. It is probably the most common screening approach used, though it is usually not used to develop emission estimates. Screening measurements can be made upwind and downwind and directly above waste material using real-time instruments to estimate potential for air emissions. Air concentration measurements made at short distances (<40 meters) downwind of the waste can be used to indicate the potential for air emissions from the site. Downwind measurements should be corrected for any instrument bias and upwind interferences. Meteorological factors can influence the air concentration of volatiles and particulate matter so field notes must include on-site observations and meteorological conditions during testing.

- Air Monitoring/Modeling. Air monitoring and modeling methods are equivalent to the indirect emissions measurement methods except that the samples are collected at greater distances from the waste, typically at the fenceline or property line, and the sampling locations are not as clustered. If meteorological data are collected concurrently, these data can be used to validate dispersion model estimates and estimate the potential for contaminants to reach off-site receptors. However, they may be limited by the sensitivity of the instrumental measurement used and the dispersion and dilution of the air emission. Unless estimates of off-site impact potential are needed, fenceline monitoring is not recommended for the screening study.

- Emissions (Predictive) Modeling. Emissions modeling can be used if the preliminary assessment has provided fairly detailed information that can be input into a model. The model estimates can usually be improved by using air emissions data from the site. The Superfund Exposure Assessment Manual (SEAMS) models are appropriate as a screening technology for landfills, and the Mackay model is appropriate for lagoons. Modeling has the obvious advantage of being an off-site activity.

Once an appropriate screening method and associated equipment/instruments are selected, a technical approach to applying the method should be developed. The Data Quality Objective For Remedial Response Activities (13) can provide assistance in designing the site screening. Again, each unit of a combined site must be studied independently. This may involve the use of different screening methods for the various site units.

Quality control should be an integral part of any screening study, and direction in developing and documenting a quality assurance project plan can be obtained from the interim Guidelines and Specifications For Preparing Quality Assurance Project Plans.(14) One very useful exercise in the design of the screening study is a "dry-run" survey, including a mock exercise involving data use. This will help in determining if the technical approach will satisfy the intended objective of obtaining an estimate of the potential for air emissions from the site.

After design is completed, the site screening approach should be circulated for review and then modified, as necessary.

Once the site screening has been completed, the screening data should be evaluated to determine if further data (in-depth measurements) are required for the site characterization. Screening data may consist of a concentration number representing volatile content (headspace sampler or analysis of headspace above the waste in a bottled sample) or a preliminary BEE (indirect emission measurement/model estimate, air monitoring/model estimate, predictive model estimate). The BEE should be an addition of all of the site units if the units are studied individually. Any emissions data for disturbed waste should not be included in the BEE and do not have to be summed separately since the site mitigation planning will probably use the disturbed site emission estimates on a unit basis in developing mitigations for "operable units."

Absolute criteria against which to compare these BEE data are not available. Estimated ambient levels (determined from the BEEs) can be compared to state ambient air toxic levels and to EPA cancer risk values if available.

If high levels of air emissions from the site are possible and more detailed information is required to meet the APA objectives, then site characterization should be conducted using in-depth technologies to develop representative BEEs. If, however, little or no potential for air emissions surfaces from the data or if screening BEEs provide enough information for a site manager to evaluate air emissions, in-depth BEEs development may not be necessary in the site characterization.

3.1.5 Design and Conduct the In-Depth Site Characterization

The activities to design and conduct an in-depth study are similar to those described in Section 3.1.4 for screening except that in-depth assessment methods rather than screening methods are used. The steps are:

- Determine the feasibility of obtaining the detailed BEEs.
- Select appropriate in-depth methods, indicator species, and applicable equipment/instrumentation.
- Design the site characterization technical approach and test plan, including the QA/QC program.
- Circulate the detailed technical approach and test plan for review and ensure it addresses the site-specific objective(s).
- Conduct the site characterization program and document the findings.
- Determine if the BEE data are sufficient and adequate for site mitigation decisions. If adequate, document them; if inadequate, evaluate the data needs and reiterate, as necessary. Re-evaluate and document.

In-depth techniques for developing BEEs are summarized in Table 11 and presented in detail in Section 4. In general, direct emissions measurement methods offer several advantages over the other approaches and are considered to be the preferred methods for most sites. With the exception of the wind tunnel, the direct measurement methods applicable to landfills and lagoons are limited to volatiles. These technologies generate BEEs as a function of the site conditions and can be used with a variety of analytical techniques. Measurements at the source (waste) will be the highest in concentration compared to the other measurement techniques. The direct emission measurement methods are not suited to sites that are heterogeneous.

TABLE 11. TYPES OF IN-DEPTH METHODS FOR ESTIMATING EMISSIONS*

- Direct Emissions Measurement
  - Surface Emission Isolation Flux Chamber
  - Portable Wind Tunnels
  - Soil Vapor Probe
  - Soil Vapor Monitoring Well
  - Downhole Emission Flux Chamber
  - Vent Sampling
- Indirect Emissions Measurement
  - Concentration Profile
  - Transect
- Air Monitoring/Modeling
  - Concentration Profile
  - Transect
  - Exposure Profile
- Emissions (Predictive) Modeling
  - Any model using site-specific values
  - RTI and Scholl Canyon (Landfills)
  - Thibodeaux, Parker, and Heck (Lagoons)

* See Section 4 for more detailed information.

For those applications where the waste is not homogeneous, is inaccessible, or consists of multiple sources which need not be individually studied, the indirect methods are preferable to direct methods. Total site air emissions can be obtained and used to estimate BEEs and disturbed waste emission data. Indirect methods are susceptible to meteorological influences and require analytical techniques with greater sensitivity than those used for direct measurements. Also, upwind interferences can create problems.

Air monitoring/modeling methods are similar to indirect methods, but used farther downwind. They have the same applicability and limitations, except that even lower air concentrations can be expected farther downwind. This approach is not generally recommended unless fenceline data are required for other needs. Air monitoring/modeling methods are discussed in detail in Volume IV of this series of guidance manuals.

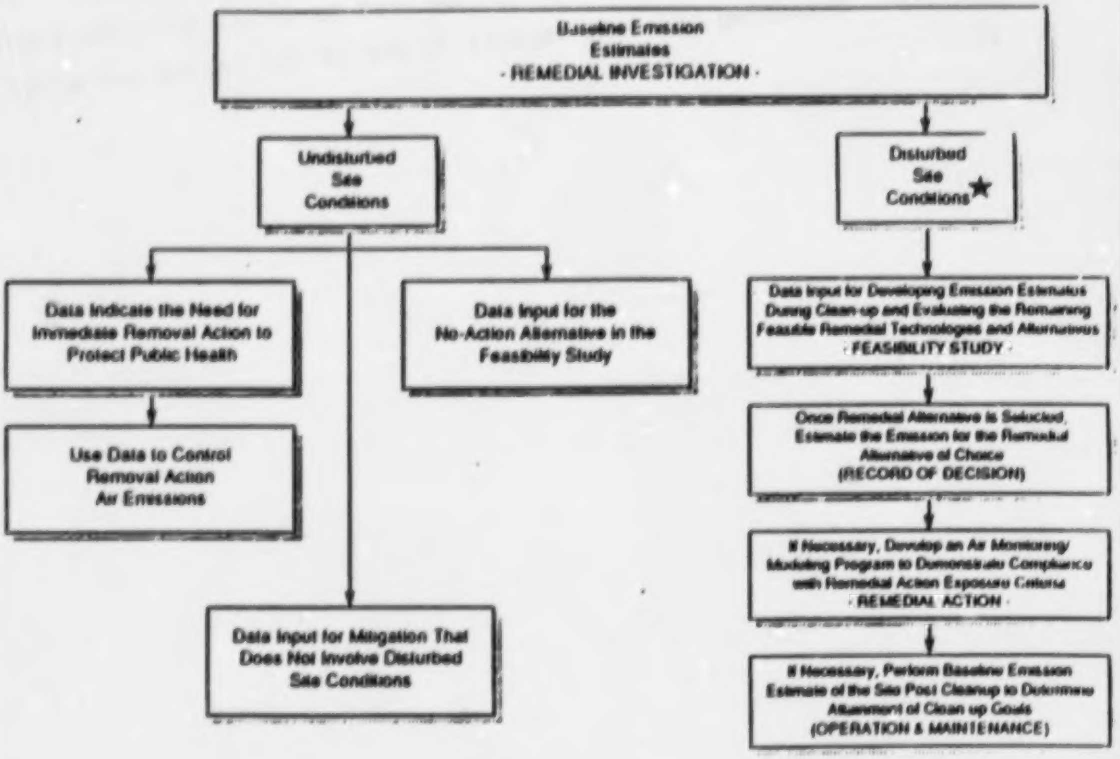
Emissions (predictive) modeling can be used; however, site-specific data, particularly diffusion coefficient data, are often necessary to obtain representative BEEs. These data may be difficult and expensive to gather. In addition, demonstrating the validity of the models for specific applications may be difficult. It is emphasized that site-specific data are required for site characterization; the use of literature data should be limited, if possible.

Once the in-depth site characterization has been designed and conducted, the BEEs should be evaluated and documented. Data should be organized like the screening assessment data, but these data are generally better estimates of the emissions potential since more sophisticated technologies are used.

If the baseline emission estimates are considered necessary and sufficient to satisfy the project needs, then the field studies for the APA are complete and these data are documented. If the BEEs are considered inadequate or additional APA data are required, then follow-on site characterization should be designed and conducted.

3.2 USE OF THE BEEs IN THE MITIGATION PROCESS

Figure 8 illustrates how the BEEs fit in the CERCLA mitigation process. Data uses for non-NPL sites will probably be very similar to those identified in Figure 8. BEEs generated in the remedial investigation can be used in two ways. First, BEE data provide information regarding the potential air quality impact and health risk(s) posed by the site should the no-action remedial alternative be selected. Essentially, this is the air impact that can be expected from the site over time if the site is left alone. Thus, the BEEs used in this way may help justify the decision to mitigate the site. These data may also indicate the need for an immediate removal action to protect the public from possible air contaminants.


Baseline Emission
Estimates
- REMEDIAL INVESTIGATION -
Undisturbed
Site
Conditions
Disturbed
Site
Conditions★
Data Indicate the Need for Immediate Removal Action to Protect Public Health
Use Data to Control Removal Action Air Emissions
Data Input for the No-Action Alternative in the Feasibility Study
Data Input for Mitigation That Does Not Involve Disturbed Site Conditions
Data Input for Developing Emission Estimates During Clean-up and Evaluating the Remaining Feasible Remedial Technologies and Alternatives
- FEASIBILITY STUDY -
Once Remedial Alternative is Selected, Estimate the Emission for the Remedial Alternative of Choice
(RECORD OF DECISION)
If Necessary, Develop an Air Monitoring/ Modeling Program to Demonstrate Compliance with Remedial Action Exposure Criteria
- REMEDIAL ACTION -
If Necessary, Perform Baseline Emission Estimate of the Site Post Cleanup to Determine Attainment of Clean up Goals
(OPERATION & MAINTENANCE)

★As previously noted, measurments of emissions from exposed or disturbed wastes can generally be performed during the RI using the same techniques used for performing baseline emission measurements.

Figure 8. Use of the BEEs data in site mitigation.

Second, data for the disturbed site are necessary to estimate short- impacts to air quality and risks to on-site workers and neighboring reside during cleanup. These data assist in the evaluation of remedial alternati considered in the feasibility study. Remember that this protocol is desig specifically to develop BEEs (and disturbed emission estimates). These da along with dispersion modeling, can be used to assess off-site impacts to a quality. Assessing off-site impacts is one of the topics addressed in Volu IV.

SECTION 4
AIR EMISSION MEASUREMENT TECHNIQUES

Section 4 describes recommended air emission assessment techniques (methods) for landfills and lagoons. The recommended techniques are organized into four types of approaches: direct emission measurement techniques, indirect emission measurement techniques, air monitoring/modeling techniques, and emissions (predictive) modeling techniques. Each type of approach is further divided into two classes: screening methods, and in-depth assessment methods. The screening methods provide some level of air emission assessment but may not accurately represent the site's potential for air emissions. The in-depth assessment methods are much more rigorous and generally provide a more accurate estimate of the potential for air emissions from the site. Screening techniques are typically used in the site inspection stage of the RI, whereas in-depth assessment techniques are typically used during site characterization.

4.1 GENERAL CONSIDERATIONS

General considerations for the various air emission measurement techniques are given below before individual air monitoring and modeling techniques are described. The methods are first compared, followed by a discussion of the uses of the emission estimates. A discussion of how to determine worst-case conditions for estimating emissions is then given.

4.1.1 Comparison of Techniques

A comparison and relative ranking of the air emission assessment techniques are provided here to assist the user in selecting an appropriate assessment technique. Comparisons and relative rankings for screening techniques are summarized in Tables 12 and 13. A more detailed comparison of various predictive models is given later in Section 4.5. Similar information for the in-depth techniques is presented in Tables 14 and 15. The comparisons of available techniques indicate the applicability of each technique and the

TABLE 12. COMPARISON OF SCREENING TECHNIQUES

Screening Techniques	"Preferred" Technology	Applicable Species		Typical Data Outputs			
		Volatile	Particulate Matter	Indicates Potential Emissions	Flux Rate	Soil Vapor Concentration	Ambient Air Concentration
Head Space Samplers		X			X	X	
Head Space Analysis of Bottled Samples	X	X		X		X	
Upwind/Downwind	X	X	X		X		X
Mass Balance		X			X		
Real-Time Instrument Survey	X	X	X	X			X
Predictive Models	X	X	X		X		

TABLE 13. RELATIVE RANKING FOR SCREENING TECHNIQUES

	Cost Parameters[a]				Quality Parameters[b]		
Screening Techniques	Equipment	Manpower	Time	Analytical	Accuracy	Complexity	Variability
Head Space Samplers	4	1	3	5	2	8	2
Head Space Analysis of Bottled Samples	3	1	3	5	2	8	1
Upwind/Downwind	5	1	3	8	3	6	3
Mass Balance	1	1	3	10	2	10	2
Real-Time Instrument Survey	3	1	3	1	3	10	4
Predictive Models	3	1	5	1	5	5	5

[a] Ranking is on a 1 to 10 scale (1 being lowest cost, 10 being highest cost); Manpower ranking is the number of people required.

[b] Scale:
Accuracy 1 = least accurate, 10 = most accurate
Complexity 1 = most complex, 10 = least complex
Variability 1 = most variable, 10 = least variable

TABLE 14. COMPARISON OF IN-DEPTH TECHNIQUES

		Applicable Species		Typical Data Outputs				
Screening Technique	"Preferred" Techniques	Volatiles	Particulate Matter	Baseline Flux Rate	Disturbed Flux Rate	Soil Vapor Concentration	Ambient Air Concentration	Point Source Emission Rate
Emission Isolation Flux Chamber	X	X		X	X			
Portable Wind Tunnel		X	X	X	X			
Soil Vapor Probes	X	X				X		
Soil Vapor Monitoring Well		X			X	X		
Downhole Flux Chamber	X	X			X			
Vent Sampling		X						X
Concentration Profile		X	X	X	X		X	
Transect	X	X	X	X	X		X	
Boundry Layer Emission Monitoring		X	X	X	X		X	
Predictive Models	X	X	X	X	X			

TABLE 15. RELATIVE RANKING FOR IN-DEPTH TECHNIQUES

	Cost Parameter[a]				Quality Parameters[b]		
In-Depth Techniques	Equipment	Manpower	Time	Analytical	Accuracy	Complexity	Variability
Emission Isolation Flux Chamber	5	2	5	6	9	5	5
Portable Wind Tunnel	7	2	5	6	9	6	5
Soil Vapor Probes	5	2	3	6	5	4	3
Soil Vapor Monitoring Well	10	2	7	6	8	4	4
Downhole Chamber	6	2	7	6	8	4	3
Vent Sampling	5	2	2	6	10	10	10
Concentration Profile	10	3	10	10	7	1	3
Transect	8	3	10	10	5	3	3
Boundry Layer Emission Monitoring	8	2	10	6	6	3	3
Predictive Models	3	1	5	1	5	5	5

[a] Ranking is on a 1 to 10 scale (1 = lowest cost, 10 = highest cost); manpower ranking is the number of people required.

[b] Scale: Accuracy 1 = least accurate, 10 = most accurate
Complexity 1 = most complex, 10 = least complex
Variability 1 = most variable, 10 = least variable

type of output data that each technique will provide. Where possible "preferred" techniques are identified and recommended for use. The preferred techniques are not necessarily those with the highest numerical rankings in the tables, since not all the ranking factors are equally important; rather they are the techniques that have proved to be the most cost-effective in past field applications. The preferred technique, however, will not always be the best choice of assessment technique for every application. The intent of identifing preferred techniques is to assist the RPM or site manager by identifying those techniques that are thought to be preferrable for the majority of sites.

The type of output data that each technique provides varies significantly. For example, some screening techniques are designed to measure emission flux rates and ambient air concentrations, while others will simply indicate if there is a potential for emissions (i.e. a qualtative output). Data output from the in-depth techniques can also vary.

The techniques are also ranked according to their relative cost (i.e. equipment, manpower, time, and analytical) and data quality (i.e. accuracy, complexity, and variability). Among the screening techniques, upwind/downwind monitoring has the highest relative cost while mass balances and predictive models provide the lowest cost alternative. However, as one would expect, there is a trade-off between cost and data quality. The same is true of the in-depth techniques. The selection of an appropriate technique must be based on the data requirements of the site inspection and site characterization stages of the RI, as well as on the cost of the available techniques.

The use of screening versus in-depth techniques will depend on the ultimate uses of the data. Screening techniques are generally employed at all sites to assess the potential for air emissions or the approximate levels of contaminants to which on-site workers are exposed. In-depth techniques, because of their cost and comlexity, are generally only employed at sites where air emissions are considered likely to be a potential problem.

One area of emerging technology is the use of remote sensing systems for measuring background levels of emissions. There has been only limited evaluation of these techniques for Superfund or hazardous waste applications. These techniques are still undergoing rapid development, but are generally not sufficiently sensitive yet to measure large numbers of volatile and semivolatile compounds at concentration levels of interest from a risk assessment standpoint. Therefore, these techniques are not included in Section 4. An overview of the currently available types of remote sensing systems, however, is included as Appendix E of this manual. Remote sensing has the potential to become an important tool for estimating baseline emissions.

4.1.2 Uses of Emission Estimates

The various monitoring and modeling techniques presented in this manual provide either a relative indication of emissions potential (e.g. soil vapor concentration) or an emission rate estimate. The relative indications of emissions potential are primarily useful as a screening tool. The data can yield useful information about the types of emissions at a given site, the general magnitude of these emissions, and the spatial variability of these emissions, i.e. the presence of "hot spots". This information, in turn, is input to the process of evaluating whether more detailed emissions data are necessary.

The emission rates generated from monitoring or modeling activities generally provide data for a portion of the site or equivalent area (see 2.1.3) for a given time frame. The primary use of such data is for risk assessment purposes to evaluate the potential effect of baseline emissions on the health and safety of on-site workers and the surrounding populace. For on-site workers, the emissions from a given equivalent area are usually of greatest concern. For off-site receptors, the summed emissions from all the equivalent areas at the site need to be considered. A simple arithmetic sum should be sufficient, but the time dependence of the emission processes should be considered. The maximum emissions for different equivalent units may not take place in all units during a given time frame.

Emission rates are given in terms of mass of pollutants per unit area per given time frame. Emissions over several different time frames may of interest, including:

1) Maximum emissions during any 15-minute period;
2) Maximum emissions during any 60-minute period;
3) Average emissions during an 8-hour work period;
4) Average emissions during a 24-hour period;
5) Average annual emissions; and
6) Average exposure over a 70 year period.

The time frames of interest will depend on the objectives of the air pathway analysis. In general, the emissions will be compared to either health-based standards as part of a risk assessment or to regulatory emisson standards to assess compliance. The six time frames listed above include peak, short-term, and long-term periods as commonly defined in health-based standards and emission standards.

It is usually necessary to convert emission rates to concentrations at the receptors of interest, in order to assess health and safety concerns arising from air quality impacts. This conversion must be made for conducting quantitative risk assessments. The most valid means to accomplish this is to use the emission rate as a source (input) term to an atmospheric dispersion model. The models identified by the EPA for volatile compounds and for particulate matter are discussed in Volume IV of this series (3). The downwind concentrations determined from the dispersion modeling should be compared to any existing downwind ambient air data as a check of the modeling results. Dispersion models are of limited use for estimating dispersion over very short distances, such as may be the case for on-site personnel working in close proximity to emission sources. The results of the emission rate estimates coupled with dispersion modeling are typically compared to established action levels to determine if the site emissions pose a potential health or safety risk or used as input to a risk assessment.

The advantage of using emission rate estimates rather than performing air monitoring at the locations of interest (e.g. fenceline) is the additional information and flexibility the emission rate data provide. Air monitoring results are valid for the locations used for the specific metorological conditions encountered. Emission rates determined from monitoring or modeling can be used to estimate ambient air concentrations under a wide variety of meteorological conditions and for almost any receptor locations of interest. The emission rates can also generally be modified to account for changes in the emitting area or the levels of emissions without the need for additional field work. As new information on the nature of the site becomes available, the emission rates can be adjusted to reflect this additional information. For example, if removal actions are instigated or a soil cover is added, the emitting area or absolute rate can be changed to reflect these changes. Additional data developed during the RI/FS process can also be used to modify the inputs to predictive models for estimating emissions or their dispersion. For example, if new receptors are identified, it would be simpler to run new model cases than to perform additional ambient air monitoring to estimate the concentration levels at the new receptors.

4.1.3 Determining Worst-Case Conditions

The desciptions of the monitoring and modeling techniques in the following subsections include information on the limitations of the techniques. All of the techniques are only useful for certain ranges of conditions and will not provide data of acceptable uncertainty if applied to situations that exceed the worst-case conditions. The acceptable worst-case conditions vary from technique to technique and must be determined from the available literature and field experience.

The monitoring techniques generally have specific validation criteria. For the indirect monitoring techniques, this involves some set of metorological conditions that must be met. For the direct monitoring techniques, this usually involves some evaluation of the spatial and temporal variability in emissions to determine if the series of direct emission measurements are adequate to determine the average emissions for the entire site or some portion of the site.

The modeling techniques generally do not have specific validation criteria, but the validity of the modeling results are dependent on the uncertainty associated with the model inputs. Use of the models requires knowledge of the types of compounds present and their concentrations in the soil or water, along with information on the physical nature of the site and the applicable meteorological conditions. The exact inputs required vary greatly from model to model. The evaluation of whether or not the inputs are adequate for modeling purposes is rarely clear-cut; the worst-case conditions for modeling are generally not well defined. Therefore, it is generally necessary that field data be collected to assess the validity of the results from predictive models.

4.2 DIRECT EMISSION MEASUREMENT TECHNIQUES

A general discussion of direct measurement techniques is followed by descriptions of the individual techniques. The direct emission measurement techniques presented in this section are:

Screening Techniques--
4.2.1 Head Space Sampler
4.2.2 Head Space Analysis of Bottled Sample

In-Depth Techniques--
4.2.3 Emission Isolation Flux Chamber
4.2.4 Portable Wind Tunnels
4.2.5 Soil Vapor Probes
4.2.6 Soil Vapor Monitoring Well
4.2.7 Downhole Chamber
4.2.8 Vent Sampling

Direct emission measurement techniques are often the best techniques for investigating the air pathway. The emission rates that are typically generated can be plugged into dispersion models to predict ambient concentrations at various locations under varying meteorological conditions. The techniques generally consist of isolating or covering a small section of the site surface or subsurface using a chamber or enclosure. The concentration of emissions produced by the isolated surface is measured within the chamber or from an outlet line. These concentration measurements, along with other technique-specific parameters, are then used to calculate an emission flux or relative concentration value. The emission flux (rate per area) can generally be related to an emission rate for the entire source.

The types of volatile or particulate species that can be measured by the techniques are essentially unrestricted; their measurement depends on the sampling media selected and analysis technique rather than the emission measurement technique. However, few of the techniques are applicable to both volatile and particulate emission rate measurement. Selection of sampling media and analysis techniques are addressed in Volume IV of this series. Direct emission measurement techniques can be used to determine the emission rate variability of a site by performing multiple measurements at selected locations across the site. In addition, these techniques allow for the evaluation of individual waste areas at the site so that the investigation can focus on those areas with the greatest potential emissions.

The cost of the direct emission measurement techniques varies considerably. Most of the direct techniques, however, are cost-effective relative to other approaches since several measurements can usually be made in a given day. Real-time instruments can be used with all the direct techniques to provide immediate data for decision-making during the sampling program, and for the relative ranking of the emission rate at locations across the site. This procedure can be used to reduce the number of samples requiring laboratory analysis by screening for those samples with significant concentrations.

Direct emission measurement techniques, as a class of assessment techniques, are generally preferable to other classes of techniques because they have been proven to be a relatively cost-effective approach for obtaining emission rate and concentration data and they avoid the necessity of modeling to develop BEEs. Direct emission measurement techniques and equipment are generally relatively simple and straightforward.

4.2.1 Head Space Samplers (Screening Technique)

Head space samplers can be used as a chamber to isolate part of the emission source surface.(15,16,17) The quantity or concentration of vapors and/or gas emitted from the surface that build up in the chamber over a period of time is measured, rather than measuring a rate. The head space sampler technique was a predecessor to the emission isolation flux chamber described in 4.2.3.

Head space samplers may be operated in one of two modes, referred to as static and dynamic modes. In the static mode, the sampling enclosure is placed over the emitting surface for a given period of time.(15) The enclosure may be purged initially with clean air or nitrogen. Surface emissions then enter the chamber from the exposed surface and are allowed to concentrate in the chamber before sample collection.

A time-integrated emission flux for the static mode is calculated as:(15)

$$E_i = (C_i \; V_E)/(t \; A) \qquad \text{(Eq. 1)}$$

where
E_i = emission flux for component i (ug/m^2-sec);
C_i = concentration of component i (ug/m^3);
V_E = volume of the enclosure (m^3);
t = length of time enclosure is in place (sec); and
A = surface area enclosed by chamber (m^2).

The build-up of gas species within the chamber improves the sensitivity of the method relative to ambient air sampling. However, the accuracy of the calculated emission rate is dependent on the duration of sampling relative to the time required to reach steady-state concentrations within the chamber. For long sampling periods, the concentration gradient of the soil/air interface is reduced and the emission flux is underestimated. Also, instantaneous changes in the flux cannot be measured.

In the dynamic mode, the sampling enclosure also is placed over the emitting surface for a given time period and the chamber may be initially purged with clean air or nitrogen. However, collected emissions are continuously withdrawn from the enclosure.(15) The chamber can be operated with a second port allowing ambient air to enter the chamber to prevent a negative pressure within the chamber. The emitted species is concentrated on sampling media or may be continuously monitored. When the sample is concentrated on the sampling media (i.e., sorbent), the emission flux is calculated as:(15)

$$E_i = (C_i\ V_s)/(A\ t) \qquad \text{(Eq. 2)}$$

where E_i = emission flux for component i (ug/m^2-sec);
C_i = concentration of component i (ug/m^3);
V_s = total volume of sample withdrawn (m^3);
t = length of sampling interval (sec); and
A = surface area enclosed by chamber (m^2).

An advantage of the dynamic mode is that the sampling duration and air sampling rate can be varied to adjust the volume of air sampled in order to achieve the required analytical sensitivities. The disadvantage of operating in the dynamic mode is that as the atmosphere within the enclosure is withdrawn, the emission flux value may be affected. This can occur by the addition of bulk flow of the soil gas into the chamber or, alternately, air entrainment occurring within the enclosure because of leakage at the enclosure's bottom edge, or by air moving through the soil at the enclosure's bottom edge. If a second port is used to allow atmospheric air to enter, a means of removing volatiles from the atmospheric air must be used.

The major advantage of the technique is that the method is simple. The enclosures are typically 55 gallon drums sawed in half lengthwise or a similarly simple enclosure. The method is independent of meteorological conditions (except for changes in barometric pressure). The analysis can involve sampling the headspace with a portable analyzer after specified time intervals. The field crew can consist of a single technician.

Applicability--

The emission isolation flux chamber (see Section 4.2.3) is preferred to head space samplers except where the emission flux is expected to be extremely low. Under these conditions, use of head space samplers in static mode for long intervals (possibly days) may allow emission fluxes to be measured by the head space sampling technique where other techniques may fail to produce a measurable emission flux.

Head space samplers are applicable to emission flux measurement from all forms of solid area sources including landfills, open dumps, and waste piles, and for homogenous, quiescent lagoons. The technique can be used at open and closed landfills, with or without internal gas generation. The technique can be used to assess emission rates from cracks in the surface cover and from vents that have minimal or no volumetric flow. The technique is applicable both for undisturbed and disturbed site conditions.

Limitations--

As previously mentioned, head space samplers may enhance (dynamic mode) or suppress (static mode) the emission flux. The dynamic mode also may be subject to air entrainment resulting in deceptively low emission flux values. The technique does not assess the effects of wind speed on the emission flux. For lagoons, removal of air from the chamber will induce a pressure change unless make-up air is able to enter the chamber. The chamber will require some type of support of flotation system, and this may be affected by waves or agitation.

Head space samplers are not applicable to the measurement of particulate emission fluxes. Also, no validation of the technique has not been reported.

4.2.2 Headspace Analysis of Bottled Samples (Screening Technique)

Headspace analysis of bottled sample is a preferred technique for field screening of wastes and soils to determine their relative emissions potential. In this method, liquid, soil, or waste from the site surface or subsurface is collected. The material is immediately placed in a sampling container, typically 1-liter or a 40 mL volatile organic analysis (VOA) vial with septa;

and the container sealed. Transferring the soil or waste immediately after collection into the sample container to prevent loss of volatiles is the key to successful use of the technique. The container is allowed to stand for a given period of time, typically 5 to 30 minutes. The container lid is then cracked open and the probe of a field instrument is inserted to determine if soil-vapors are present. Syringes can be used to withdraw gas samples via parts of the VOA vial septa for more sophisticated analysis techniques. Typical field instruments used include portable flame ionization detectors, photoionization detectors, combustion meters, and colorimetric tubes.

A second type of headspace analysis involves analyzing the headspace gas or extracted solids of a soil waste core. To obtain a sample to measure the headspace, an undisturbed core is collected using an auger or by driving a tube into the ground. The sample is then sealed in a sample container with minimal headspace.

The core sampler shown in Figure 9 consists of a brass core sleeve which is pressed into the soil to a sufficient depth to fill the sampler but not compress the sample. After excess soil is removed, the sleeve is sealed with a Teflon-lined cap. The samples are stored at room temperature. Headspace gas is removed from the core by a syringe and analyzed by GC.

Applicability--

The headspace analysis is a useful screening technique for all types of soil or waste which have a volatile component. Some experimentation may be required to determine the optimal time to allow for volatilization to occur before measurement. The technique can be used to identify surface contamination boundaries, select sampling locations for detailed techniques, and identify health and safety concerns.

The technique is best suited for measuring adsorbed organics, although it can also be effective with free organics in the pore space if the material is rapidly transferred to the sample container, or if tube or core samplers are used.

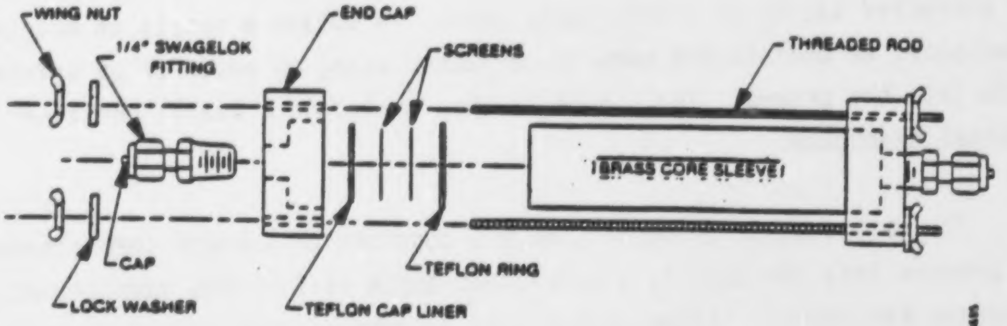

WING NUT
1/4" SWAGELOK FITTING
END CAP
SCREENS
THREADED ROD
BRASS CORE SLEEVE
CAP
LOCK WASHER
TEFLON CAP LINER
TEFLON RING

Figure 9. Schematic diagram of a soil core sample sleeve.

Limitations--

The technique does not provide for calculation of an emission rate, but rather identifies soils and wastes which are potential source of air emissions. The technique generally only provides qualitative data on species type, however, species specific data can be obtained if suitable analytical techniques are selected. The technique is only applicable to undisturbed conditions. The technique is not applicable to particulate emissions.

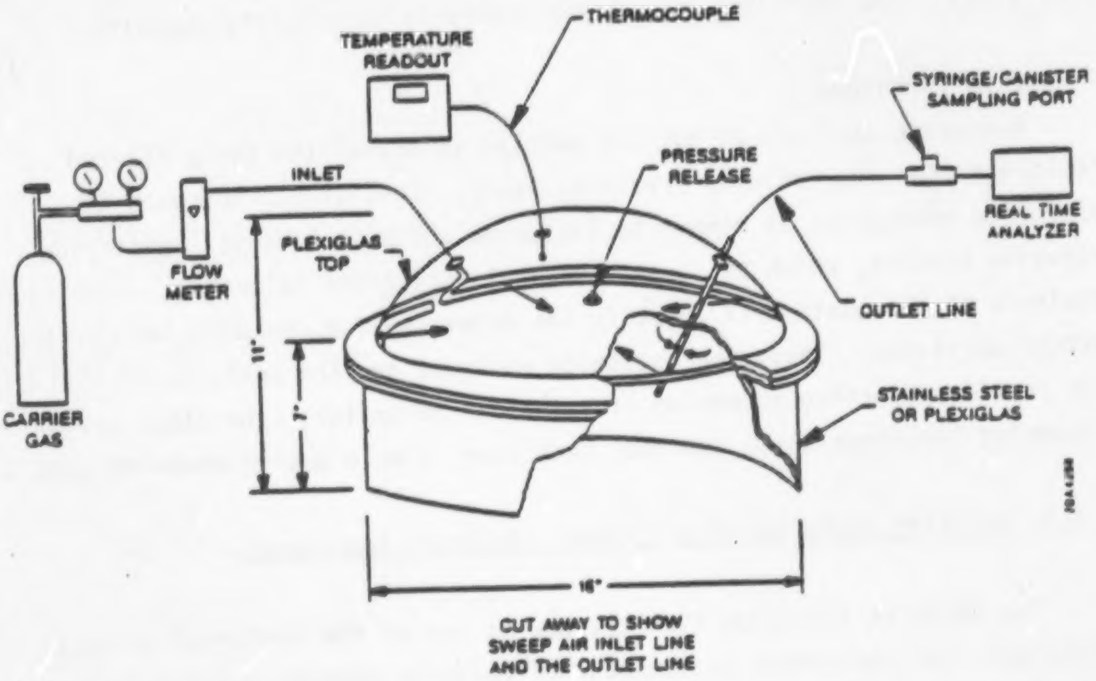
Preferred Technique--

Headspace analysis of bottled samples is one of the two preferred techniques for the emission screening study. This direct approach is preferred because it is simple to implement and effective at identifying volatile content, which represents volatile emissions potential. Chemical analysis of the waste will identify the potential for contaminated particulate matter emissions. Thus, the headspace analysis and the analysis of the waste can provide effective screening of emissions potential. The other preferred screening technique is an indirect technique, simple upwind/downwind sampling.

4.2.3 Emission Isolation Flux Chamber (In-Depth Technique)

The emission isolation flux chamber is one of the preferred in-depth techniques for the direct measurement of volatile species emission rates.(18-23) The technique uses a surface enclosure (flux chamber) to isolate a known surface area for emission flux (rate per area) measurement. The emission isolation flux chamber for solid surfaces is illustrated in Figure 10 and for liquid surfaces in Figure 11.

Emissions enter the open bottom of chamber from the exposed surface. Clean, dry sweep air is added to the chamber at a metered rate. Within the chamber, the sweep air is mixed with emitted vapors and gases by the physical design of the sweep air inlet. The sweep air creates a slight wind velocity at the emitting surface, preventing a build up of the emission concentration in the boundary layer directly above the surface. The exit port is used for measurement of the concentration of the air within the chamber or for sampling and subsequent analysis. A pressure relief port in the enclosure prevents pressure build up within the chamber that might otherwise occur when sampling



THERMOCOUPLE
TEMPERATURE READOUT
SYRINGE/CANISTER SAMPLING PORT
PRESSURE RELEASE
INLET
REAL TIME ANALYZER
PLEXIGLAS TOP
FLOW METER
OUTLET LINE
11"
7"
CARRIER GAS
STAINLESS STEEL OR PLEXIGLAS
16"
CUT AWAY TO SHOW SWEEP AIR INLET LINE AND THE OUTLET LINE

Figure 10. A cutaway diagram of the emission isolation flux chamber and support equipment for solid surfaces.

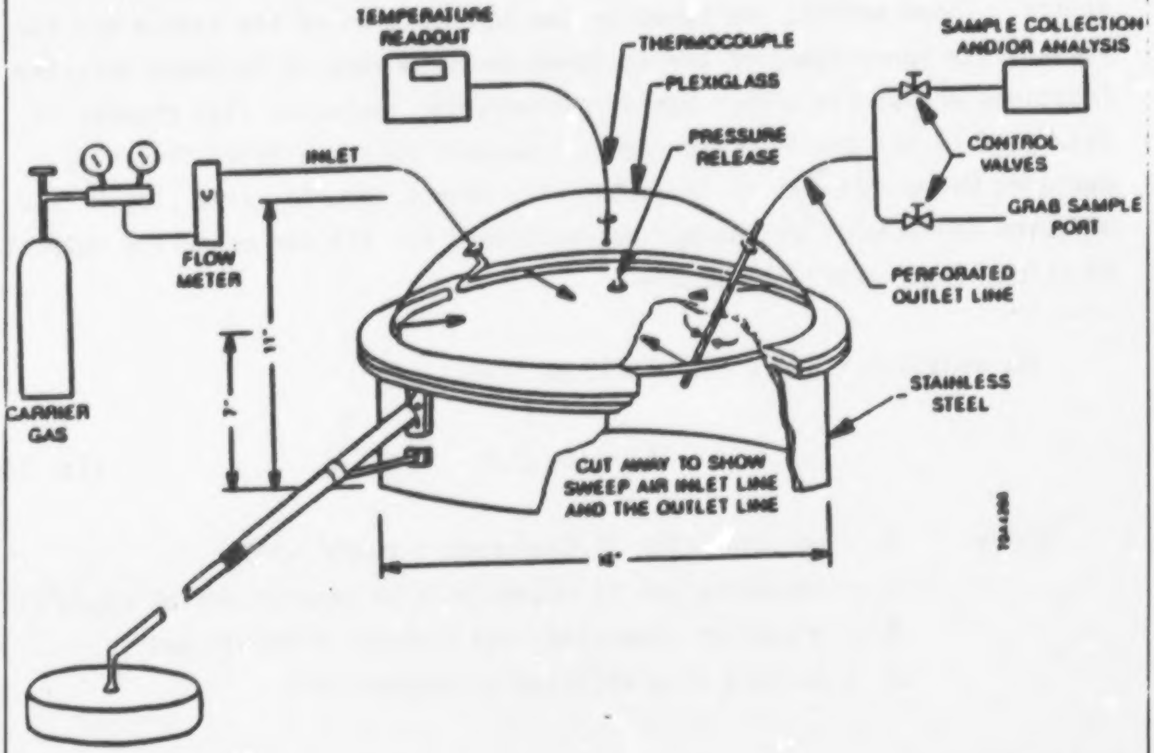

TEMPERATURE READOUT
THERMOCOUPLE
PLEXIGLASS
PRESSURE RELEASE
SAMPLE COLLECTION AND/OR ANALYSIS
CONTROL VALVES
GRAB SAMPLE PORT
PERFORATED OUTLET LINE
INLET
FLOW METER
CARRIER GAS
11"
7"
STAINLESS STEEL
CUT AWAY TO SHOW SWEEP AIR INLET LINE AND THE OUTLET LINE
16"
T04280

Figure 11. A cutaway diagram of the surface emission isolation flux chamber and support equipment for liquid surfaces.

liquid surfaces. A positive or negative pressure in the enclosure could affect the emission event and, thus, the assessment of the emission flux. For lagoons, a support or flotation system is necessary.

The technique directly measures essentially an instantaneous emission flow (flux) from that surface. The emission flux is calculated from the surface area isolated, the sweep air flow rate, and the emission concentration. Statistical methods are used to determine the number of measurement locations required to characterize the emission from an area source. These methods are based on the surface area of the source and the variability (precision) of the measured emission rate at randomly selected locations across the site. Use of the emission isolation flux chamber is described in the draft "Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber User's Guide (23)." The emission isolation flux chamber was validated for EPA for measuring volatile emissions from landfills.(22,23)

The emission flux is calculated as (23):

$$E_i = (C_i\ Q)/A \qquad \text{(Eq. 3)}$$

where E_i = emission flux of component i (ug/m^2-min);
C_i = concentration of component i at chamber outlet (ug/m^3);
Q = sweep air flow rate into chamber (m^3/min); and
A = surface area enclosed by chamber (m^2).

Applicability--

The emission isolation flux chamber is applicable to emission flux measurement from all types of area sources including lagoons, landfills, open dumps, and waste piles. The technique can be used at open and closed landfills, with or without internal gas generation. The technique can be used to assess emission rates from cracks in the surface cover and from vents that have minimal or no volumetric flow.

The technique is applicable both for undisturbed and disturbed site conditions, and for the testing of emissions control techniques. The technique can be used to satisfy data needs for all phases of the RI/FS process, as well as post-remediation monitoring and, therefore, can provide directly comparable data throughout the process.

Limitations--

The emission fluxes of volatile species may be enhanced or suppressed since the flux chamber alters the environmental conditions (e.g., wind speed) at the sampling locations. The technique does not assess the effects of wind speed on the emission rate.

The technique is not particularly well suited to large emission sources with a high degree of heterogeniety. Comparison of sample data and variability estimates can determine the number of sampling locations needed to determine representative area emissions. Also, the technique is not applicable to the measurement of particulate emission fluxes.

Preferred Technique--

The emission isolation flux chamber is a preferred technique for developing in-depth BEEs. As discussed, the advantages generally out-weigh the limitations of the technique. The technique is well documented in the user's guide and well characterized.

4.2.4 Portable Wind Tunnels (In-Depth Technique)

Wind tunnels are in-depth techniques used to directly measure the emission rate of erodible material. They also can be used to measure the emission flux of volatile compounds. In either application, measurements can be made under varying wind conditions to examine the effect of wind speed on emissions. The required equipment consists of portable, open-bottomed enclosures used to isolate a known surface area, a blower used to simulate wind conditions, and sampling devices.

The Cowherd wind tunnel, shown in Figure 12, is a portable wind tunnel developed for "in situ measurement of emissions from representative test surfaces under predetermined wind conditions"(24). The tunnel was developed to measure particulate matter emissions from open waste piles. "The open-floored test section of the portable wind tunnel is placed directly over the surface to be tested. Air is drawn through the tunnel at controlled velocities. The exit air stream from the test section passes through a circular duct fitted with a sampling probe at the down-stream end. Air is drawn through the probe isokinetically by a high-volume sampling train"(24). The sampling train consists of a trapper probe, cyclone precollector, parallel-slot cascade impactor, backup filter, and high volume motor. Air flow is provided by a blower located downstream of the sampling train.

The authors state that, "although a portable wind tunnel does not generate the larger scales of turbulent motion found in the atmosphere, the turbulent boundary layer formed within the tunnel simulates the smaller scales of atmospheric turbulence. It is the smaller scale turbulence which penetrates the wind flow in direct contact with the pile surface and contributes to the particle entrainment mechanisms"(24).

The emission flux is calculated from the isolated surface area, emission concentration, simulated wind speed, and time period during which particulates are collected. Because the emission concentration is collected over time, the technique measures the overall (time integrated) emission rate rather than the emission flux. Varying the simulated wind speed between measurements allows for development of a weighted average emission rate. This is preferred to using an average wind speed because the total erosion may be greatly influenced by infrequent periods of high wind speed.

The loss of erodible material is calculated as (24):

$$E_i = (C_i \; Q \; t)/A \qquad \text{(Eq. 4)}$$

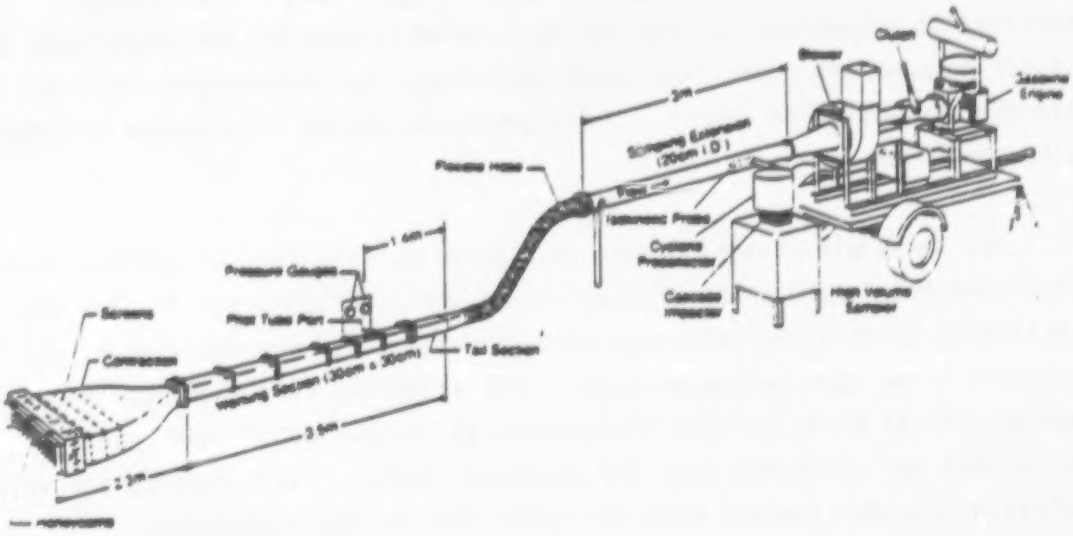

Blower
Clutch
Gasoline Engine
3m
Sampling Extension (20cm I.D.)
Flexible Hose
Flow
Isokinetic Probe
Cyclone Precollector
Cascade Impactor
High Volume Sampler
1.4m
Pressure Gauges
Pitot Tube Port
Screens
Contraction
Tail Section
Working Section (30cm x 30cm)
3.9m
2.3m
Honeycomb

Figure 12. Illustration of MRI wind tunnel.

where E_i = emission rate of component i (g/m^2);
C_i = average particulate concentration of component i in tunnel exit stream (g/m^3);
Q = tunnel flow rate (m^3/sec);
t = duration of sampling (sec); and
A = exposed test area (m^2).

Elimination of the time factor in the calculation will provide an emission flux on a unit area per time basis (g/m^2-sec). The average particulate concentration (C_i) may be reduced to account for background dust levels by sampling under light wind conditions and subtracting the resulting average concentration from C_i values generated during simulations of higher wind conditions.

The Astle wind tunnel, shown in Figure 13, is a form of surface enclosure developed for "measurement of odor source strength"(25); but it also may be applicable to volatile emissions measurement. This portable wind tunnel consists of an open-bottom enclosure that is placed over the emitting surface. Ambient air is blown through the chamber at typical wind speed rates (e.g., 1 to 15 mph) and collected near the enclosure outlet. Test results for volatile emission rate measurement were not identified in the literature.

The emission flux is calculated from the simulated wind speed, emission concentration, and surface area isolated. Varying the wind speed between measurements allows for development of a weighted average emission rate. The measurement is essentially instantaneous.

The emission flux calculation is (25):

$$E_i = (C_i\ Q)/A \qquad \text{(Eq. 5)}$$

where E_i = emission flux of component i (ug/m^2-sec);
C_i = concentration of component i (ug/m^3);
Q = air flow rate through tunnel (m^3/sec); and
A = surface area enclosed by the tunnel (m^2).

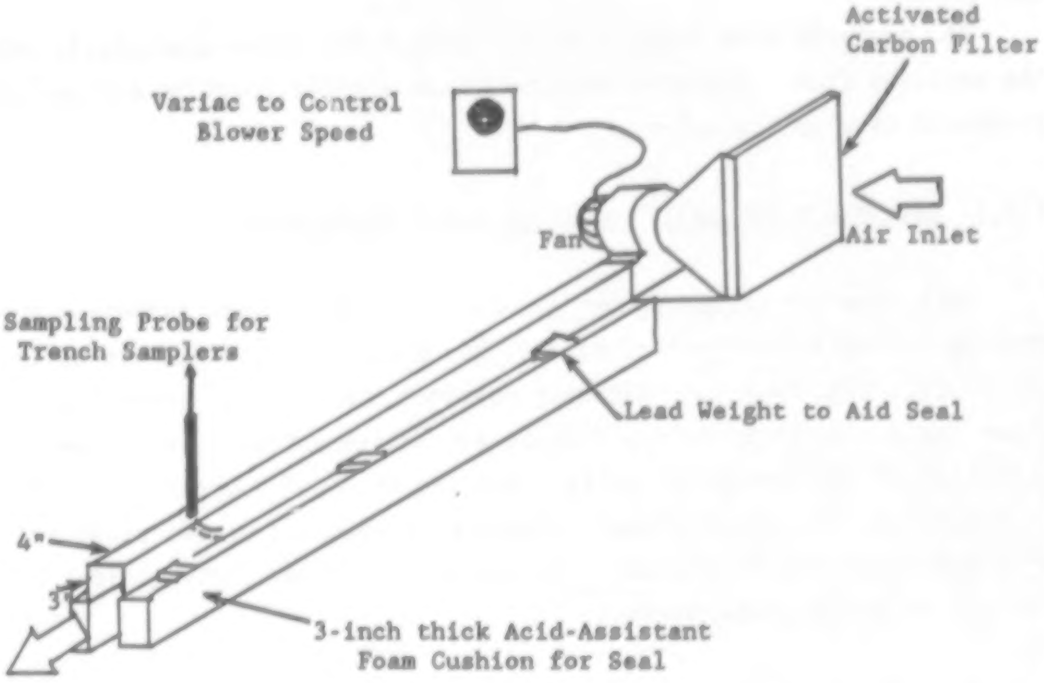

Activated
Carbon Filter
Variac to Control
Blower Speed
Fan
Air Inlet
Sampling Probe for
Trench Samplers
Lead Weight to Aid Seal
4"
3"
3-inch thick Acid-Assistant
Foam Cushion for Seal

Figure 13. Schematic of portable wind tunnel.

Applicability--

Wind tunnels are applicable to emission measurements from all forms of solid area sources, including quiescent lagoons, landfills, open dumps, and waste piles. The technique can be used at open and closed landfills, with or without internal gas generation. The technique is applicable both for undisturbed and disturbed site conditions.

Limitations--

The portable wind tunnels do not account for macro-atmospheric effects on the emission flux. Repeated measurement at a given location may deplete the reservoir of erodible material.

4.2.5 Soil Vapor (Ground) Probes (In-Depth Technique)

Soil vapor or ground probes are a preferred in-depth technique for mapping the horizontal extent of soil gas plumes in near-surface soils (26,27,28). The technique directly measures the soil gas concentration at a given depth. As such, it can provide a relative estimate of the emissions potential of the subsurface soils. One variation of a ground probe is shown in Figure 14. Probes with small chambers or openings at the probe end have also been used (see Figure 15). Reference 27 includes descriptions of a wide variety of ground probe designs.

The probe assembly is driven into the ground to the desired sampling depth. Emissions enter the probe from the exposed subsurface soil, depending on the design via existing openings or by raising the pipe away from the drive tip. Generally, either a small aliquot of soil gas is collected to avoid disturbing the soil gas equilibrium or a known amount of soil-gas is pumped from the probe. The concentration measured is used as a relative indicator of contamination and potential emissions. Clean, dry sweep air can be added to the probe at a metered rate if a relative emission "flux" is desired. The flux cannot be measured with any degree of confidence since the exact surface area of exposed waste is not known.

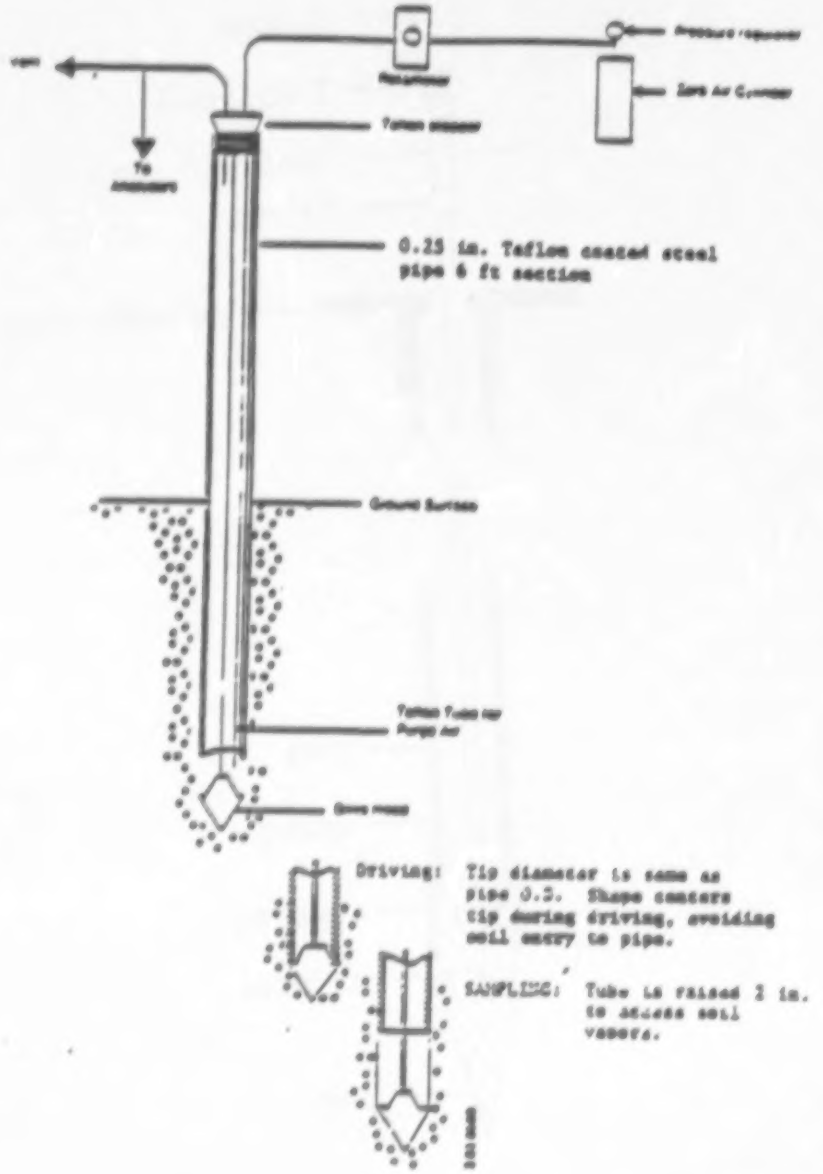

Vent
To Analyzers
Rotameter
Pressure regulator
Zero Air Cylinder
Teflon stopper
0.25 in. Teflon coated steel pipe 6 ft section
Ground Surface
Teflon Tube for Purge Air
Drive Point
Driving: Tip diameter is same as pipe O.D. Shape centers tip during driving, avoiding soil entry to pipe.
SAMPLING: Tube is raised 2 in. to access soil vapors.

Figure 14. Schematic diagram of a simple ground probe.

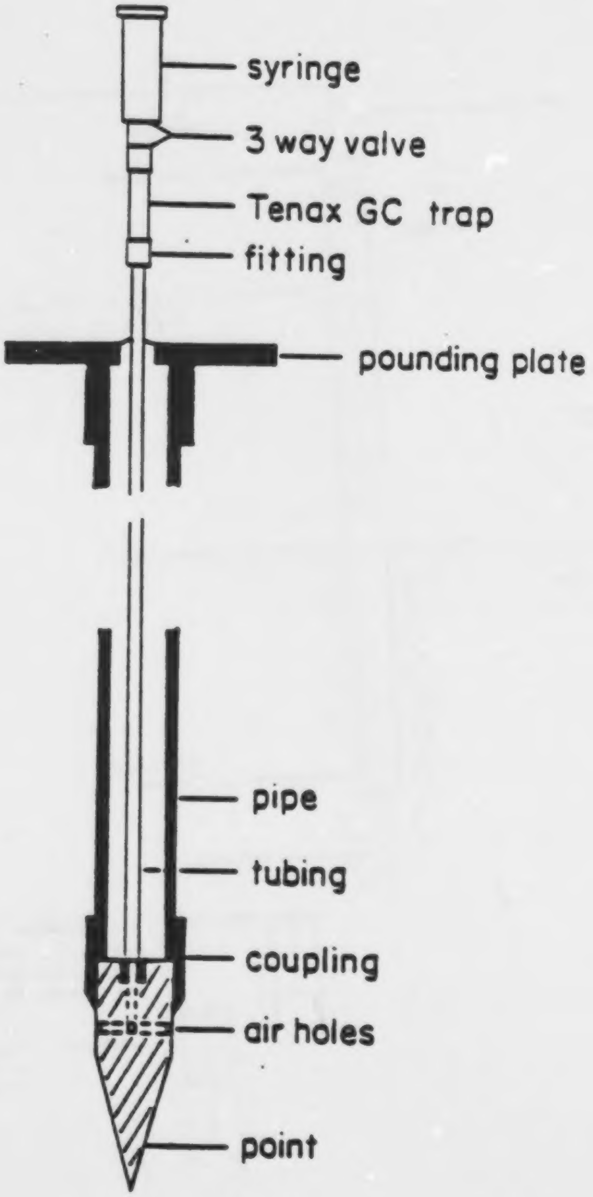

syringe
3 way valve
Tenax GC trap
fitting
pounding plate
pipe
tubing
coupling
air holes
point

Figure 15. Ground probe design with minimal internal volume.

The major advantage of the technique is that it allows for rapid mapping of the horizontal extent of soil gas plumes in near-surface soils. Generally, mapping is performed by measuring the soil gas concentration without use of sweep air. The mapping can be used to determine the approximate subsurface boundaries of buried waste or immiscible liquids floating on the water table. Ground probes are very useful for investigating the migration of soil vapors as part of the air pathway analyses.

It is not necessary, although desirable, to know the waste composition to use the technique. Knowing the waste composition will help in the selection of appropriate instrumentation or sampling apparatus.

Applicability--

The technique can be used to map soil gas plumes to indicate approximate waste boundaries or soil gas migration routes. Ground probes are also applicable to the measurement of potential volatile emissions from disturbed subsurface soil and waste. The technique measures the emissions that would occur if the subsurface soil or waste were disturbed by excavation. The technique also can be used to measure the soil gas concentration by operating the probe without sweep air. Soil gas concentration measurements can be used as an input to predictive models, as discussed in Section 4.4.

The technique is applicable for estimating emissions from solid waste sites, including open and closed landfills, with or without internal gas generation, open dumps, and waste piles. The technique also can be used to estimate emissions below the edges of tanks, buildings, ponds, etc., by driving the probe into the soil at an angle. In addition, ground probes can be hand- or machine-driven. Hand-driven probes allow measurements to be performed in areas where surface access by machines is not available.

Limitations--

Ground probes do not measure the undisturbed emission rate or flux from a waste site. Rather, the technique identifies the relative concentration of vapors in the sub-surface. This information can be used to estimate locations that may have significant air emisisons during any soil excavation or other site disturbance.

Use of ground probes is generally limited to near-surface soils, typically less than 12 feet deep. However, the operational depth will depend on site and equipment characteristics which limit the ability to insert the probe. Ground probes do not measure particulate emission rates.

4.2.6 Soil Vapor Monitoring Wells (In-Depth Technique)

Soil vapor monitoring wells (29) are used to measure the emission flux from subsurface soil and waste and to monitor soil vapor concentrations and the effects of soil vapor remedial actions. The in-depth technique uses a monitoring well consisting of a screened chamber installed during drilling activities. As such, the soil vapor monitoring well is a permanent or semi-permanent structure. Figure 16 illustrates a typical soil vapor monitoring well.

Soil vapor monitoring wells are installed through the annulus of a hollow-stem auger. The well consists of an enclosed, screened chamber with sampling lines leading to the surface. The chamber is enclosed in a sand pack. The well casing is used to provide support during well construction and protection for the sampling lines, but soil vapors and gases do not contact the well casing. Soil vapors and gases enter the soil vapor monitoring well through the chamber screen. Within the chamber, the vapor and gases are mixed with clean, dry sweep air. The resulting mixture is withdrawn through the exit port to measure the emission concentration and/or for sampling and subsequent analysis. The sweep air flow rate is selected to approximate the instrumentation or sampling apparatus flow rate.

Because the measured emission concentration is directly related to an emissions event from an isolated surface over an essentially instantaneous time period, the technique can be used to estimate the emission flux from the isolated soil surface. The estimated emission flux is calculated from the assumed surface area isolated, the sweep air flow rate, and the emission concentration.

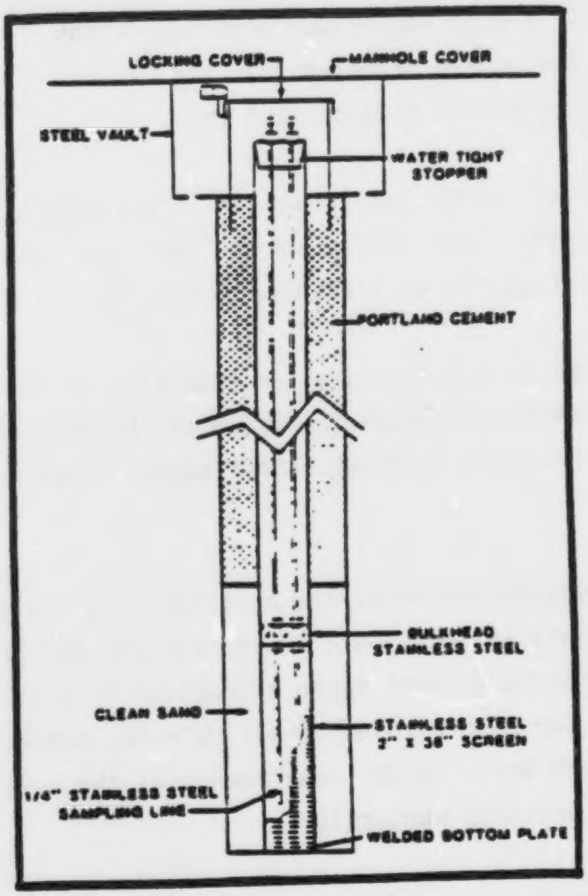

LOCKING COVER
MANHOLE COVER
STEEL VAULT
WATER TIGHT STOPPER
PORTLAND CEMENT
BULKHEAD STAINLESS STEEL
CLEAN SAND
STAINLESS STEEL 2" X 36" SCREEN
1/4" STAINLESS STEEL SAMPLING LINE
WELDED BOTTOM PLATE

Figure 16. Vapor monitoring well constructions. (Not to scale)

The emission flux is calculated as (26):

$$E_i = \frac{C_i Q}{A} \qquad \text{(Eq. 6)}$$

where E_i = emission flux for component i (ug/m^2-min);
C_i = concentration of component i (ug/m^3);
Q = sweep air flow rate (m^3/min); and
A = exposed surface area (m^2) = πdh
d = screen diameter (m); and
h = height of sand pack (m).

Typically, soil vapor monitoring wells are used to measure the soil vapor concentration, rather than the emission flux. The soil vapor concentration is measured by operating the well without sweep air.

The technique is not dependent on knowledge of the emissions process or the waste composition, although knowledge of the waste composition will help in selecting appropriate instrumentation and/or sampling apparatus.

Applicability--

Soil vapor monitoring wells are applicable to the monitoring of soil vapor concentrations and vapor migration, and are the preferred method for monitoring the effects of soil vapor extraction systems. Soil vapor monitoring wells may also be used to estimate the potential emission flux from subsurface soil and waste in the same manner as the soil vapor probes discussed in the previous subsection.

The technique is applicable to the estimation of emission fluxes and concentrations from open and closed landfills, with and without internal gas generation, and open dumps. The technique also is applicable to measurement of emission concentration from immiscible liquids floating on the water table.

Limitations--

Soil vapor monitoring wells do not measure the undisturbed emission flux, but rather the flux that would occur during site disturbance. The technique is not applicable to the measurement of particulate emission fluxes. The actual exposed surface area is an assumed or estimated value.

4.2.7 Downhole Emissions Flux Chamber (In-Depth Technique)

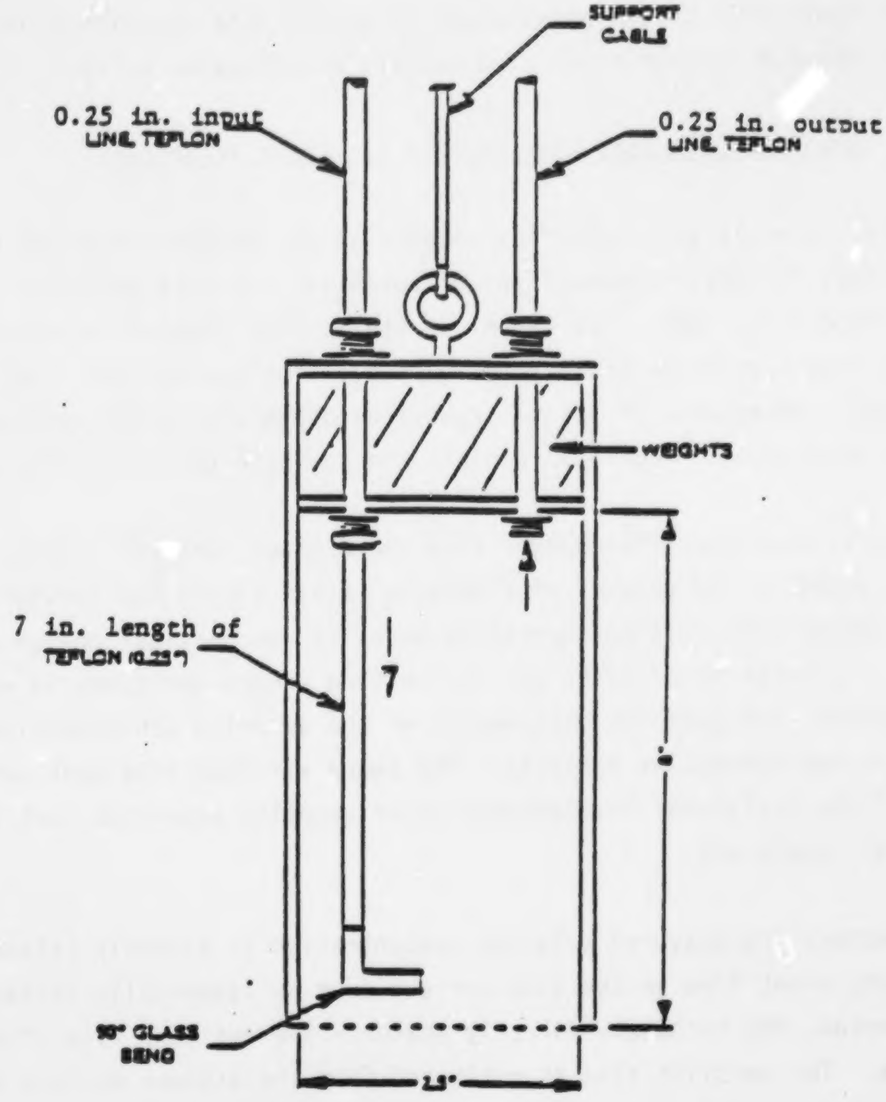
The downhole emissions flux chamber is one of the preferred in-depth techniques for direct measurement of potential volatile emissions from subsurface soils (30). The technique uses a flux chamber to measure emission fluxes from subsurface soils exposed by drilling operations. The chamber isolates a known area of soil at a desired depth within the annulus of a hollow-stem auger. Figure 17 depicts the downhole emissions flux chamber.

Emissions enter the chamber from the exposed surface. Clean, dry sweep air is added to the chamber at a metered rate. Within the chamber, the sweep air is mixed with emitted vapors and gases by the physical design of the air inlet. The mixture of sweep air and emitted vapors and gases is withdrawn through the exit port for measurement of the emission concentration or for sampling and subsequent analysis. The sweep air flow rate must match the flow rate of the analytical instrumentation or sampling apparatus that is used to withdraw sample gas.

Because the measured emission concentration is directly related to an emissions event from an isolated surface over an essentially instantaneous time period, the technique directly measures the emission flow (flux) from the surface. The emission flux is estimated from the assumed surface area exposed, the sweep air flow rate, and the emission concentration.

The emission flux is calculated as (30):

$$E_i = \frac{C_i Q}{A} \qquad \text{(Eq. 7)}$$



SUPPORT CABLE
0.25 in. input LINE TEFLON
0.25 in. output LINE TEFLON
WEIGHTS
7 in. length of TEFLON (0.25")
7
90° GLASS BEND
2.5"

Figure 17. Schematic diagram of the downhole emissions flux chamber.

where E_i = emission flux of component i (ug/m^2-min);
C_i = concentration of component i (ug/m^3);
Q = sweep air flow rate (m^3/min); and
A = exposed surface area (m^2).

The major advantage of the technique is that it allows the investigation of subsurface areas without excavation.

Although desirable, knowledge of the waste composition is not necessary to use the technique to assess the air pathway. However, knowledge of the waste composition will help in the selection of appropriate emission concentration measurement instruments.

Applicability--

The downhole flux chamber is applicable to measurement of the potential emissions from subsurface soil and waste. The technique estimates the emission flux that could occur if the subsurface soil or waste were exposed by excavation. Therefore, the technique is most suitable for determining emissions potential for remedial alternatives evaluation and/or site disturbances. The technique is useful for characterizing the volatile species present in subsurface waste or soil layers. The technique also can be used to measure the soil gas concentration by operating the chamber without sweep air. However, for shallow depths, ground probes are preferred for gas concentration measurements (see Section 4.2.5).

The technique is applicable for estimating emission fluxes from all materials that can be investigated using hollow-stem auguring techniques. The technique can be used at open and closed landfills, with or without internal gas generation, and at open dumps.

Limitations--

The downhole emissions flux chamber does not measure the baseline emission flux from a waste site. Rather, the technique measures the potential emission rate that could occur during site disturbance.

The emission flux of volatile species may be enhanced or suppressed if the sweep air flow rate does not closely match the flow rate of the sample gas extraction system. The downhole flux chamber cannot be used to measure particulate emission rates.

Preferred Technique--

The downhole emissions flux chamber is a preferred technique for characterizing potential emissions from subsurface disturbed waste. Most investigations involve subsurface sampling using a hollow-stem auger and drill rig and downhole flux chamber work can be incorporated in the investigation.

4.2.8 Vent Sampling (In-Depth Technique)

Vent sampling for emissions measurement has been well documented elsewhere (32), and will not be discussed in detail here. Vent sampling is performed when the waste site contains vents with measurable flow rates (i.e., active venting, not passive venting), such as vent systems at some landfills. The in-depth technique requires measuring the emission concentration and the volumetric flow rate, typically as the exhaust velocity and cross-sectional area of the vent. Volumetric flow rates for vents (or ducts) can be obtained using the procedures given in the Code of Federal Regulations (CFR) Title 40 Part 60. Those procedures indicate how to determine the exhaust velocity and appropriate sampling location. The emission rate for a vent is calculated as (31):

$$E_i = C_i \, U \, A \qquad \text{(Eq. 8)}$$

where E_i = emission rate of component i (ug/sec);
C_i = concentration of component i (ug/m^3);
U = gas velocity through vent (m/sec); and
A = cross-sectional area of vent (m^2).

Applicability--

Vent sampling is applicable to any waste site that contains active or passive venting systems. However, active venting systems are not typical of uncontrolled hazardous waste sites. Vent sampling can be applied to landfill vents, tanks, building vents, machinery, and equipment. Where present, vents may be a major source of air emissions from the site.

Limitations--

Vent sampling using standard stack sampling technique is not applicable when the vent has minimal or no flow. For these situations, the emissions isolation flux chamber technique is preferred, provided that the chamber's cross-sectional area is larger than the vent's. When the vent is too large for use of the flux chamber, emission rate estimates may be based on head space concentration measurements at the vent outlet and diffusion in air modeling.

4.3 INDIRECT EMISSION MEASUREMENT TECHNIQUES

A general discussion of indirect measurement techniques is followed by a description of specific techniques. The indirect emission measurement techniques presented in this section are:

Screening Techniques--

- 4.3.1 Upwind/Downwind
- 4.3.2 Mass Balance
- 4.3.3 Real-Time Instrument Survey

In-Depth Techniques--

- 4.3.4 Concentration-Profile (C-P)
- 4.3.5 Transect
- 4.3.6 Boundary Layer Emission Monitoring

Indirect emission estimation techniques generally consist of measuring the ambient concentration of the emitted species and then applying these data to an equation (air dispersion model) to determine the emission rate. Many of the equations were developed to determine downwind concentrations resulting from stack emissions. For area emission sources, the source is treated as a virtual point source or line source.

The in-depth techniques are very similar as all involve clusters of ambient air samplers. The C-P technique involves a vertical array of samplers directly over the source. The transect technique involves vertical and horizontal arrays of samplers within the downwind plume. The boundary layer technique is a simplified version of the transect technique and involves several downwind samplers each at a different height. Because of their cost and complexity, the indirect, in-depth techniques are usually only used for measuing emissions of very toxic compounds, and then only if direct measurement techniques prove to be unsuitable.

A disadvantage of indirect emission measurement techniques is that the results are highly dependent on meteorological conditions. The indirect techniques require meteorological monitoring to properly align the sampling systems and to analyze the data following sample analysis. Changing meteorological conditions significantly affect the liklihood of collecting useful data. Unacceptable meteorological conditions may invalidate much of the data collected, requiring an additional sampling effort. The techniques also may produce false negative results if the emitted species are present in low concentrations which are below the sampling and analysis detection limits, or if upwind sources cannot be fully accounted for. The techniques also may not be feasible at some sites where the source area is excessively large, or where insufficient space exists downwind of the source to set up the sampling array without disturbance of the air flow pattern by obstructions (e.g., buildings, tanks).

The types of volatile and particulate species that can be measured by the techniques are essentially unrestricted and are dependent on the sampling media selected and analysis technique rather than the emission measurement technique. Sampling media and analysis techniques are not discussed here.

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The types of volatile and particulate species that can be measured by the techniques are essentially unrestricted and are dependent on the sampling media selected and analysis technique rather than the emission measurement technique. Sampling media and analysis techniques are not discussed here.

Indirect emission measurement techniques generally do not provide significant data on the emission rate variability for different locations across a site. This is because the emission concentration is measured downwind of the site after some atmospheric mixing. The techniques generally do not allow for the evaluation of individual contaminated areas at the site unless the areas are separated from one another and are not located upwind of one another.

The costs of the indirect emission measurement techniques vary considerably. The screening techniques are relatively simple and straightforward to implement, and require minimal labor and analytical costs. The in-depth techniques are complex and require considerable equipment, labor, and analysis costs. All of the techniques are subject to data loss or sampling delay due to inappropriate meteorological conditions.

4.3.1 Upwind/Downwind (Screening Technique)

The upwind/downwind technique is an indirect screening technique (33). As the name implies, in this approach one monitor (or set of monitors) is located upwind of the area source and a second monitor (or set of monitors) is located downwind. The monitoring stations include detectors or samplers for the species of interest as well as devices for measuring wind speed and direction. The upwind monitor serves as a blank or background sampling location. Concentration is measured primarily along the downwind axis only. The average surface emission flux for a particular trajectory is equal to the increase in column concentration (downwind minus upwind) divided by the transit time across the source. Transit time is a function of the distance between the source and downwind location, and the average wind velocity.

$$E.R.i = (C_D - C_U)\, \pi \sigma_y\, \sigma_z\, \bar{U} \qquad \text{(Eq. 9)}$$

where E.R.i = emission flux of species (ug/m^2-sec);
C_D = downwind concentration of species i (ug/m^3);
C_U = upwind concentration of species i (ug/m^3);
π = 3.141 ...

σ_y = lateral extent of Gaussian plume;
σ_z = vertical extent of Gaussian plume; and
$\bar{U}$ = mean wind speed (m/sec).

Applicability--

The upwind/downwind technique is applicable to emission flux measurement from all forms of area sources, including lagoons, landfills, open dump, and waste piles. The technique can be used at open and closed landfills, with or without internal gas generation. The technique is applicable both for undisturbed and disturbed site conditions, and for testing emission control techniques. The technique can be used for both volatile and particulate emission flux assessment.

The method is most frequently used when an approximate emission rate needs to be determined, and the only existing air data are ambient concentrations from a few upwind and downwind locations. Thus the emission rate can be modeled without additional field measurements being performed.

Limitations--

Upwind/downwind requires that meteorological conditions during sampling, particularly wind speed and variability, match the predetermined conditions used to select the sampling locations. The sampling locations must be on the approximate plume centerline.

The technique also assumes that the site is fairly homogeneous and that the plume is well mixed at the downwind sampling location. Therefore, the technique may not be applicable to heterogeneous sites. The technique also may not adequately collect emissions from point sources within an area source, such as cracks in landfill covers or vents, unless the plume is well mixed at the downwind sampling location. The technique is not applicable during quiescent or unstable wind conditions, and may produce false negative results during these conditions.

Preferred Technique--

The upwind/downwind screening technique is a preferred indirect technique for indirectly screening the air impacts for a site. The technique is similar to a simple real-time inspection survey, however, it is superior in that it specifies data collection consistent with a dispersion model (e.g. ISC model) so that emissions can be estimated from a variety of area sources.

4.3.2 Mass Balance (Screening Technique)

A mass balance technique can be used to indirectly determine overall, long-term emission rates by accounting for material in and out of a system and assuming the difference is lost as air emissions (31). The use of mass balance for baseline emission estimates at uncontrolled landfill or lagoon sites was not identified, but it might be applicable to waste lagoons that have minimal leaching losses. To apply the technique at an uncontrolled site, the concentration of the species contained in the lagoon (or landfill) would be measured infrequently over time along with the flowrate and concentration for any influent and effluent streams, and the emission rate would be estimated as the loss of species over time.

Applicability--

The technique would be best suited for homogenous sources containing highly volatile wastes. Application of the technique to "fresh waste", when emission rates are typically highest, is more feasible than application to "weathered" waste. The technique does not appear applicable to particulate matter emission assessment.

Limitations--

The technique is generally suited only to process applications. It is unsuited to uncontrolled waste sites because of the source types present and since the losses of material are difficult to identify due to the imprecision of the sampling and analytical methods. In addition, the mass balance technique does not distinguish between material lost to other pathways.

4.3.3 Real-Time Instrument Survey (Screening Technique)

Real-time instrument surveys are a preferred screening technique for identifying potential emission "hot-spots" or near surface waste bodies at hazardous waste sites. The survey consists of inspecting the site with real-time instruments to determine the average species concentration in the air layer directly above the site, and to identify "hot spots" with above average emission concentration. Real-time instrument surveys can also include taking headspace concentration measurements in cracks and vents. They can be used for both volatile species and particulate matter, but it is typically used for volatile species emission.

The site is inspected by placing the inlet of the real-time instrument at a specified height above the surface, typically 2-3 inches to several feet above the site surface. The site is walked on a 25-foot grid as shown in Figure 18, although the grid may be adjusted to accommodate site size. Upwind measurements are made before and after inspecting the site by measuring the ambient air at 5-feet above the site at an upwind location. Sampling for volatiles should be performed during quiescent wind conditions (i.e., average wind speed less than 5 miles per hour).

Personal-size airborne particulate monitors can be used to survey ambient particulate matter concentrations. These monitors are used in accordance with standard NIOSH industrial hygiene methods (34). Personal-size monitors whose operating principle is based on the detection of scattered electro-magnetic radiation in the near infared spectrum have been used successfully as field monitoring devices at hazardous waste sites. These monitors can also be used to collect particulate (respirable and non-respirable) samples for subsequent chemical analyses. Sampling for worst-case particulate emissions should be conducted during periods with high wind speed and dry soil conditions.

Applicability--

The real-time instrument survey is applicable to all types of hazardous waste sites, assuming sampling personnel can reach all areas of the site.

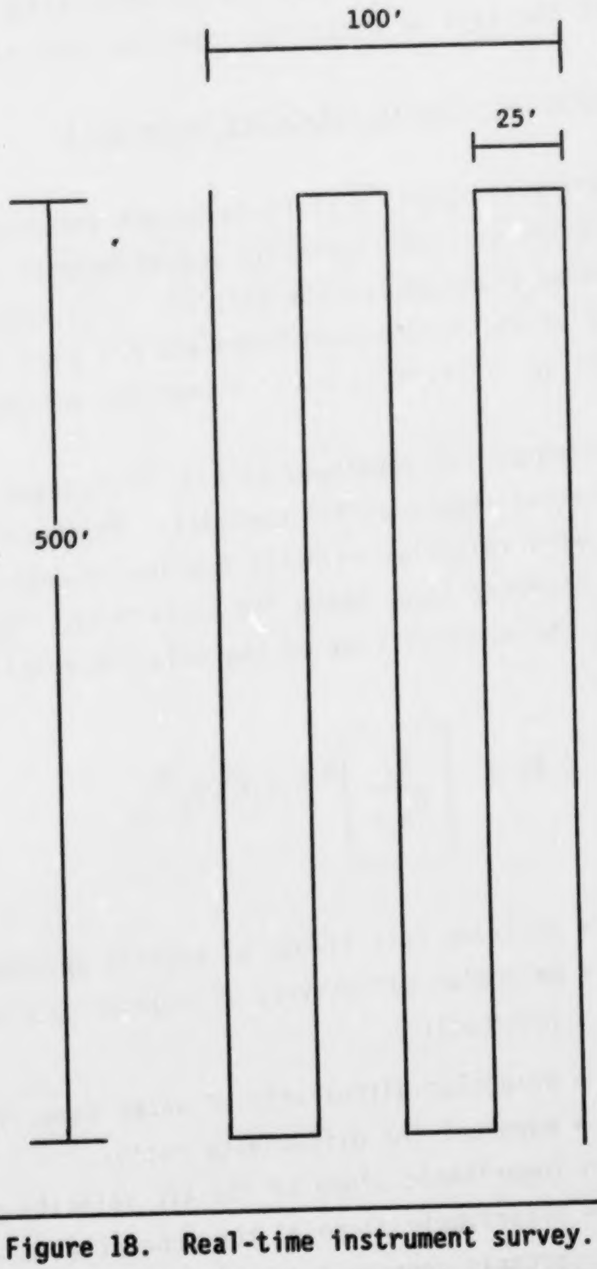


Figure 18. Real-time instrument survey.

Limitations--

The technique does not provide for calculation of an emission rate, but rather determines the number of particles per volume of air at a given receptor. This information can be used to estimate the risk from baseline particulate matter emissions at the site. The quantity of particulate matter sample that can be collected using the personal-sized monitors is small, and this may limit the type of analytical analyses that can be conducted.

4.3.4 Concentration-Profile (In-Depth Technique)

The concentration-profile (C-P) technique measures the concentration of the emitted species at logarithmically spaced heights at a downwind location on the anticipated plume centerline (21,35). This technique has been tested under a variety of waste site conditions and has been shown to produce valid results. Figure 19 illustrates the C-P sampling approach.

The C-P technique was developed by L.J. Thibodeaux and co-workers at the University of Arkansas under an EPA contract. The technique is based on measurements of wind velocity, volatile species concentration, and temperature profiles in the boundary layer above the waste body. These measurements are used to estimate the vertical flux of the volatile species as (31):

$$E_i = \left[\frac{D_i}{D_{H_2O}}\right]^n S_v S_i K^2/\phi_m{}^2 S_c \qquad \text{(Eq. 10)}$$

where E_i = emission rate (flux) of organic species i (g/cm^2-sec);

D_i = molecular diffusivity of organic species i in air (cm^2/sec);

D_{H_2O} = molecular diffusivity of water vapor in air (cm^2/sec);

n = exponent for diffusivity ratio;

S_v = logarithmic slope of the air velocity profile (cm/sec);

S_i = logarithmic slope of the concentration-profile for organic species i (g/cm^3);

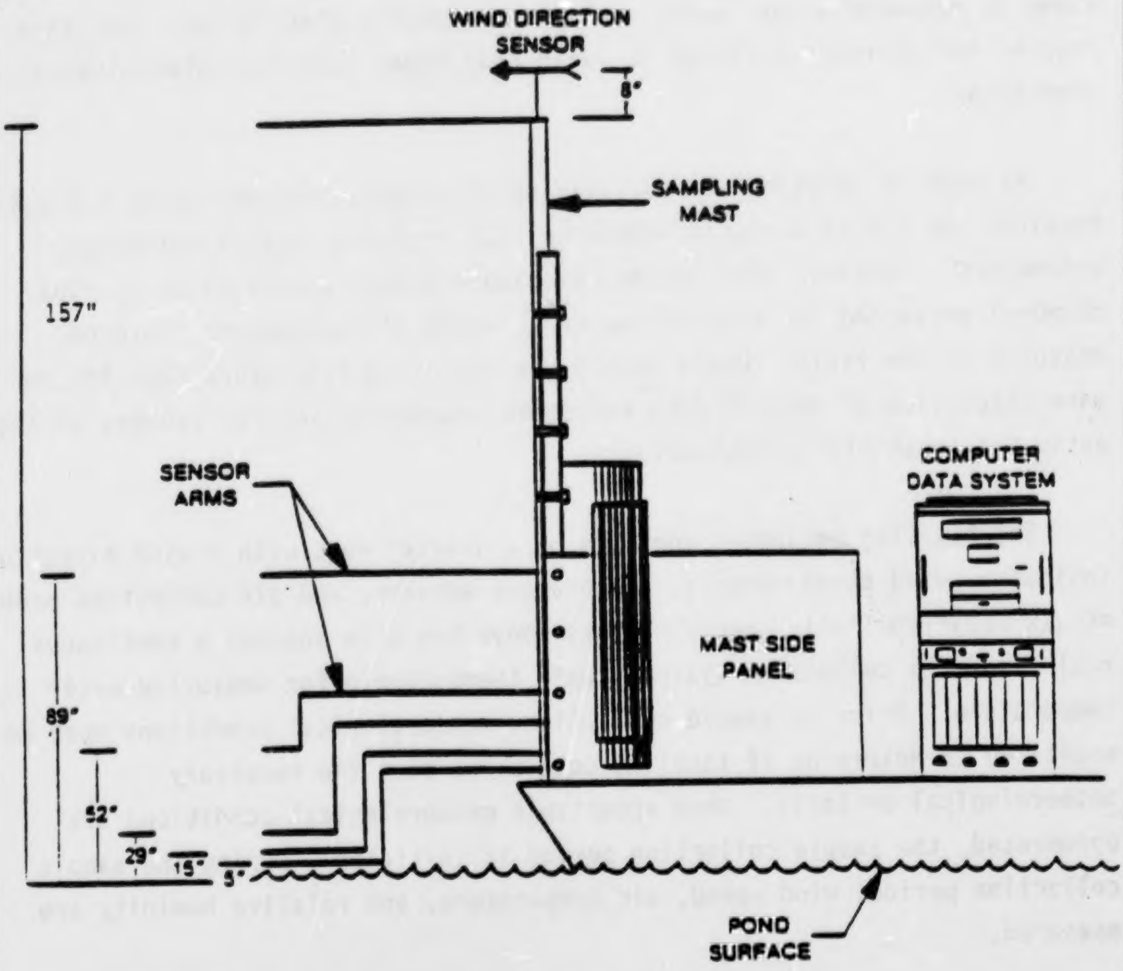

WIND DIRECTION SENSOR
8"
SAMPLING MAST
157"
COMPUTER DATA SYSTEM
SENSOR ARMS
MAST SIDE PANEL
89"
52"
29"
15"
5"
POND SURFACE

Figure 19. Mast sample collection system for C-P sampling.

K = von Karman's constant;
ϕm = Businger wind shear parameter; and
S_c = turbulent Schmidt number.

The term $(\phi_m^2 S_c)^{-1}$ represents an atmospheric stability correction factor and is expressed as a function of the Richardson number. The function is an empirical correlation which corrects the estimated emission rate for water vapor to measured values under various atmospheric stabilities. For this reason, the correction factor is valid only under specific meteorological conditions.

As seen in Equation 10, calculation of an emission rate using C-P data requires the use of a complex equation that includes several estimated aprameters. Contrast this to the relatively simple equations (e.g. flux chamber) presented for previous methods, where all parameters could be measured in the field. Users should see the cited literature (21, 35) for more discussion of the C-P data reduction procedures and for sources of the estimated constants and parameters.

The sampling equipment consists of a 4-meter mast with a wind direction indicator, wind speed sensors, temperature sensors, and air collection probes at six logarithmically spaced heights above the area source; a continuous real-time data collection system; and a thermocouple for measuring water temperature. Prior to sample collection, meteorological conditions must be monitored to determine if sampling conditions meet the necessary meteorological criteria. Once acceptable meteorological conditions are documented, the sample collection period is initiated. During the sample collection period, wind speed, air temperature, and relative humidity are measured.

Applicability--

The C-P technique is applicable to emission rate measurement from many types of large area sources including landfills, lagoons, and areas of contaminated soils. The technique is applicable for both volatile and particulate emission rate measurement. It is applicable both for undisturbed and disturbed site conditions, and for testing emission control techniques.

Limitations--

The technique requires that meteorological conditions during sampling, particularly wind speed and direction, match the predetermined conditions used to select the sampling location. The equipment required to monitor and process the meteorological conditions is much more complex than that for any of the other direct or indirect techniques. The sampling location must be on the approximate plume centerline.

The technique also assumes that the site is fairly homogeneous; therefore, the technique may not be applicable to heterogeneous sites. The technique is not applicable to sites where there is insufficient distance downwind to set up the sampling equipment. The technique also may not adequately collect emissions from point sources within an area source, such as cracks in landfill covers or vents.

The technique requires upwind sampling to account for other potential sources. Finally, the technique is not applicable during quiescent or unstable wind conditions, and may produce false negative results during these conditions.

4.3.5 Transect (In-Depth Technique)

The transect technique, also referred to as plume mapping, measures the concentration of the emitted species at several downwind locations aligned perpendicular to the anticipated plume centerline (21,36). The in-depth transect technique is an indirect emission measurement approach that has been used to measure fugitive particulate and gaseous emissions from area and line sources. This technique has been successfully tested at a variety of waste sites, including landfills. Figure 20 illustrates the transect sampling array.

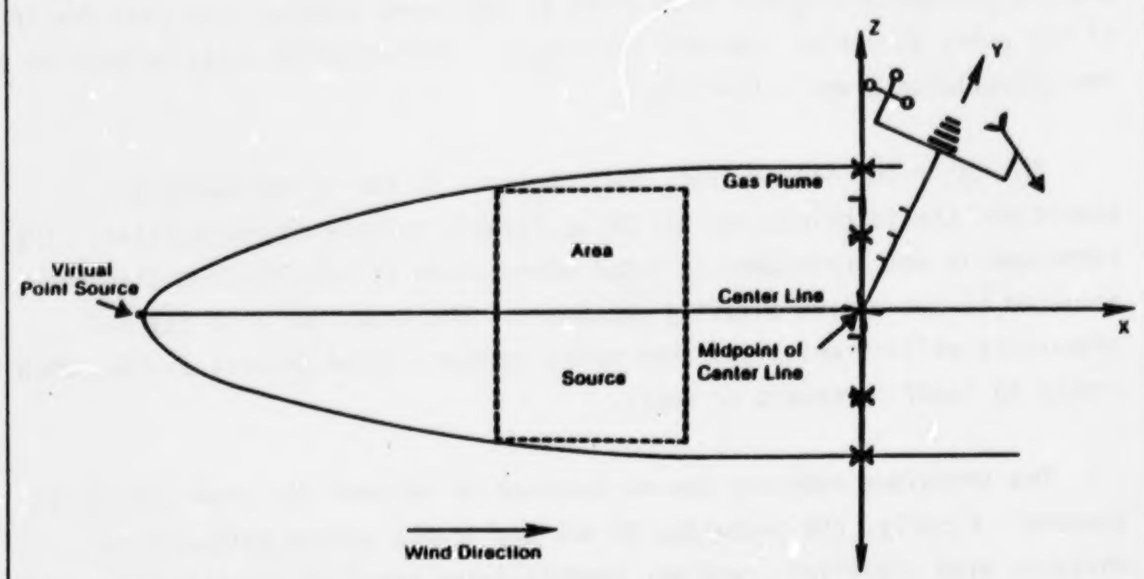

Z
Y
Gas Plume
Area
Virtual Point Source
Center Line
X
Midpoint of Center Line
Source
Wind Direction

Figure 20. Example of transect technique sampling.

The transect technique uses horizontal and vertical arrays of samplers to measure concentrations of species within the effective cross-section of the emission plume. The volatile species emission flux is then obtained by spatial integration of the measured concentrations over the assumed plume area. For volatile species, the emission flux is calculated as (21):

$$E_i = \frac{u}{A_s} \int\int_{A_p} C_i(h,w)\, dhdw \qquad \text{(Eq. 11)}$$

where E_i = emission flux of component i (ug/m^2-sec);
u = wind speed (m/sec);
A_s = surface area of emitting source (m^2);
A_p = effective cross-sectional area of the plume (m^2);
C_i = concentration of component i at point (h,w), corrected for upwind background (ug/m^3);
h = vertical distance coordinate (m); and
w = horizontal distance coordinate (m).

For particulates, the emission flux is calculated as (36):

$$E = \frac{1}{t\ A_s} \int\int_{A_p} \frac{m(h,w)}{a}\, dh\, dw \qquad \text{(Eq. 12)}$$

where E = emission flux (ug/m^2-sec);
t = sampling time (sec);
A_s = surface area of emitting source (m^2);
A_p = effective cross-sectional area of plume (m^2);
m = mass of particulates collected after correction for background concentration (ug);
h = vertical distance coordinate (m);
w = horizontal distance coordinate (m); and
a = intake area of sampler (m^2).

The cross-sectional area of the source (A_s) term can be eliminated fr both equations, if only the total site emission per time is required. An alternative equation for volatile species, based on diffusion theory and measurements, is (37):

$$E.R._i = \sum_{1}^{n} \pi X_i K_i \sigma_y \sigma_z C \bar{U} \qquad \text{(Eq. 13}$$

where $E.R._i$ = emission rate of species i (gm/sec);
X_i = peak concentration of species i (Gaussian Fit Curve);
K_i = conversion factor gm/ppm for species i;
σ_y = lateral extent of Gaussian plume;
σ_z = vertical extent of Gaussian plume;
C = instrument response factor;
π = 3.141; and
$\bar{U}$ = mean wind speed.

All parameters are obtained from field measurements. (In some instances, σ_z is estimated from σ_y). As for the C-P technique, users should see the cited literature for further guidance on the data reduction procedures. The key point to note is that the equations are relatively complex. Furthermore, terms such as σ_y and σ_z will require curve-fitting of the data and will typically have a large associated uncertainty.

The sampling equipment consists of a central 3.5-meter mast supporting three equally spaced air sampling probes, and single wind direction, wind speed, and temperature sensors at the top; and five 1.5 meter masts with single air sampling probes. The central mast is aligned downwind along the expected plume center-line. Two masts are placed on each side of the central mast perpendicular to the plume centerline at equal spacings; and one mast is used to collect air samples at an upwind location. The spacing of the associated masts is selected to cover the expected horizontal plume cross-section, as defined by observation and/or profiling with real-time analyzers. Additional sampling locations, both vertically and horizontally, can be added as required to provide sufficient coverage of the plume cross-section. Prior to sample collection, meteorological parameters must be monitored to determine if sampling conditions meet the predetermined meteorological criteria.

The transect technique is somewhat less susceptible to changing meteorological conditions than the concentration profile technique, but it does not account for the vertical dispersion of the emitted species due to their varying molecular weights. A more complex array of samplers can be employed to overcome this shortcoming, if necessary. The transect is often the preferred technique because the technique is applicable to a variety of some types and the resulting data can be more useful since the data are collected across the plume area.

Applicability--

The transect technique is applicable to emission rate measurement from all forms of area sources, including lagoons, landfills, open dumps, and waste piles.

The technique can be used for both volatile and particulate matter emission rate assessment. The technique is applicable both for undisturbed and disturbed site conditions, and for testing of emission control techniques. The technique is applicable to emissions measurement during all phases of the RI/FS process and can, therefore, provide directly comparable data throughout the process, including post remediation monitoring.

While the method assumes a relatively homogeneous site and a well mixed plume, these conditions are not necessarily required to use the method. The placement of sufficient sampling stations across the plume can allow the technique to be used at a heterogeneous site, or where the distance downwind for equipment set up is limited. However, data collected under these conditions should be carefully evaluated before use.

Limitations--

The technique requires that meteorological conditions during sampling, particularly wind speed and direction, match the predetermined conditions used to select the sampling locations. The center mast should be on the approximate plume centerline. The technique may not adequately collect emissions from point sources within an area source, such as cracks in landfill covers or vents, unless the plume is fairly well mixed at the sampling locations. The technique provides only limited vertical profiling of the plume. The technique is not applicable during quiescent or unstable wind conditions; it may produce false negative results during these conditions.

Preferred Technique--

The transect technique is a preferred indirect emission assessment technique. The technique has been used for several different types of area sources and is documented in the literature. The applicability of the technique, the conditions required for sampling and the moderate level of equipment and man-power needs suggest this technique as a preferred technique relative to other indirect approaches.

4.3.6 Boundary Layer Emission Monitoring

Boundary layer emission monitoring can be used to determine the emission rate of pollutants from large heterogenous area sources (38). The technique is similar to the transect technique in that samples are collected along an array that is perpendicular to the emission plume. However, rather than fixed sampling locations, the boundary layer technique involves a cart with three or more samplers traversing the plume with each sampler at a different height. During the plume traversing the sampling rate is adjusted to be proportional to the sine of the angle between the wind vector and the direction of the traverse path. Each run takes about an hour. The average concentrations are adjusted for any upwind concentration and then used to calculate an average vertical concentration profile. This profile is numerically integrated (with the wind velocity profile) over the contaminant boundary layer to derive an emission rate for the source.

The emission rate is (38):

$$E = \left[C_o W V_o \times 10^{-6} \right] \int_o^{Z_b} (z/10)^p (1-z/Z_b)^b \, dz \qquad \text{(Eq. 14)}$$

where E = emission rate (g/sec);

C_o = ground level concentration (ug/m^3);

W = cross-wind distance (m);

V_o = average wind speed at 10m (m/sec);

Z_b = boundary layer thickness (m);

p = exponent of wind-velocity profile; and

b = exponent of concentration profile.

Applications--

The technique can be used for measuring an emission rate from any type of source with constant emissions.

Limitations--

The method assumes that both the contaminant emission rate and the wind speed and direction are reasonably steady while sampling is conducted. The major sources of error are in the average measured wind velocity and in accounting for upwind contamination. The method should be limited to area sources that do not have significant plume buoyancy, to periods of 1-10 m/sec winds, and to sampling heights less than the depth of the mixing layer. The technique has not been validated by the EPA.

4.4 AIR MONITORING TECHNIQUES

Techniques for ambient air monitoring and indoor air monitoring are discussed below.

4.4.1 Ambient Air Monitoring

Air monitoring techniques that measure the ambient air concentration resulting from area emission sources are combined with air dispersion modeling to calculate the area source emission rate. The primary difference between indirect emission measurement techniques and air monitoring techniques is the distance at which measurements are made downwind from the source. Indirect measurements are made near the source or units of a combined site (usually on site) and may be able to distinguish between multiple units within a site, depending on the spacing between units. Air monitoring is generally performed at considerable distance downwind from the source and usually cannot distinguish between multiple units within a combined site. Air monitoring typically measures lower concentrations because the contaminant plume is subject to additional air dispersion.

The first step to use the ambient air sampling data to develop emission rate estimates is to select an air dispersion model which accurately reflects the site-specific conditions, including regional and local terrain, typical wind stability, etc. Guidance for selecting an appropriate model is given in the EPA's Guideline on Air Quality Models (39). Preferred models given in the guidance document include the Climatological Dispersion Model (CDM 2.0), Gaussian Plume Multiple Source Air Quality Algorithm (RAM), Industrial Source Complex Model (ISC), and Single Source (CRSTER) Model. A number of other potentially applicable models are included in the guidance document. Models not included in EPA's manual also may be applicable at uncontrolled hazardous waste sites, including the Point Plume Model (PTPLU), and the Gifford and Hanna Simple Box Model (40). The models are used with air monitoring and meteorological monitoring data to estimate emission rates.

Air monitoring and air dispersion models are used to determine the emission rate through an iterative process. An emission rate is first estimated for the area source. This estimated emission rate, along with meteorological data collected during air monitoring, is used to calculate a predicted downwind concentration. The predicted concentration is then compared to the measured downwind concentration. Based on this comparison, the estimated emission rate is adjusted appropriately, and the process is repeated until acceptable agreement is reached between the measured and predicted downwind air concentrations.

The air monitoring techniques that can be used to develop BEEs are listed below. These techniques were described in Section 4.3 and can be used at greater distances downwind of the emission source as air monitoring techniques.

Screening Techniques--
4.3.1 Upwind/Downwind

In-Depth Techniques--
4.3.4 Concentration-Profile
4.3.5 Transect
4.3.6 Boundary Layer Emission Monitoring

4.4.2 Indoor Air Monitoring

This section describes techniques for assessing the impacts on the indoor air quality of homes or other structures from adjacent hazardous waste sites. The primary routes for contamination of indoor air are by migration of contaminated water into or near subsurface structures and subsequent vaporization of the contaminants, and by contaminated ambient air entering into the structure. Airborne particulate matter from hazardous waste sites may settle on surfaces near the structure and may then be brought into the structure via shoes, clothing or other items. Contaminants entering the structure from this route may subsequently become airborne when they are disturbed by foot traffic, vacuuming, or other means. Assessing these impacts may involve a variety of techniques, including soil and ground water testing, and indoor and outdoor air testing.

In the absence of site-specific indoor air data, soil vapor studies are usually the most useful environmental data for assessing the potential for indoor air impacts. Soil vapor migration is the most common route of subsurface contaminant entry into homes from hazardous waste sites.

Performing soil vapor studies may also aid in identifying specific structures requiring detailed indoor air testing.

Indoor air testing programs may be burdensome on occupants and generate considerable concern, since individuals are not likely to be fully aware of the relative hazards associated with certain chemical exposures and other site-specific factors that may affect exposure patterns. These considerations dictate that indoor air programs be focused on those structures most likely affected, and that the testing methods be designed to accurately reflect airborne concentrations without being overly inconvenient or burdensome to the occupants. Occupant cooperation and agreement to participate in the testing program is an important consideration in performing these studies.

Techniques for Confirming Indoor Air Impacts - Indoor air testing programs are performed to determine the nature and extent of indoor air impacts from waste site contaminants. These testing programs may be screening studies designed to identify target analytes and specific areas or structures for additional study, or comprehensive testing and detailed analyses.

Screening studies typically involve limited sampling and analytical efforts in structures identified as high priorities, i.e. those structures most likely to be impacted. Testing may be performed by using direct reading real time analyzers that provide instantaneous measurement and feedback of the presence and concentration of selected contaminants. The most common devices used are portable flame ionization detectors (FID) and photoionization detectors (PID). These instruments are capable of detecting a wide variety of organic gases and vapors, but are not applicable to detecting non-volatile contaminants or particulate matter.

The main limitation with portable, real-time analyzers are their detection limits. These limits are based on chemical and physical properties of the specific chemical in question, and are usually in the one to five part per million range. Also, these devices are not capable of determining chemical identities. If a greater degree of sensitivity or chemical identification is required, more sensitive sample collection and laboratory analytical methods would be required.

The real time analyzers are very useful in investigating point source locations where volatile contaminants may be entering the structure, such as floor/wall junctions in grade or below grade level rooms (eg. basements) and voids or penetrations in slabs and below grade walls. Calibration of the analyzers to standard gases of analytes of interest is an essential quality control feature for these devices.

Detailed studies to identify indoor air impacts may be designed to thoroughly identify structures that may be impacted, and to examine variations in contaminant concentrations that may occur over time. Possible features of the detailed studies are summarized below:

- Sampling outdoor air in conjunction with indoor air sampling to determine the contribution of outdoor sources to indoor contamination (ie. to differentiate them from subsurface contaminant migration);

- Testing multiple rooms to determine distribution and exposure patterns within a structure;

- Inventorying products and other potential sources of target compounds (eg. cleaning, hobby and maintenance products containing volatile chemicals) to determine impacts of occupant activities on air contaminant concentrations; and

- Conducting similar testing programs in non-impacted "comparison structures" to compare the results from study area structures. Numerous sources of many indoor air contaminants have been identified inside residential and other structures, requiring testing in similar structures to determine if impacts are indeed due to the adjacent waste site. Comparison structures must be selected with construction type, building materials, indoor activities, age, heating system, and outdoor air impacts carefully considered to assure proper comparisons are made.

Detailed studies may be performed over extended periods of time to examine the influences of seasonal weather changes. This is advisable since structure ventilation and infiltration of soil vapors are affected by weather conditions. Repeat or follow-up testing may be necessary if initial testing suggests an adverse impact is present, new environmental data indicates changes in contaminant migration, or mitigation techniques are initiated.

Study design considerations - Before initiating an indoor air quality study, it is essential that proper study design features be carefully considered to assure the appropriateness of the data that are produced and the accuracy, precision and completeness of the data. Some of these considerations are:

- Collecting an adequate number of samples;
- Duration of sample collection;
- Location of sample collection in the structure; and
- Quality assurance and quality control samples.

Worst-Case Conditions - Factors influencing infiltration of contaminants into structures from adjacent hazardous waste sites can significantly affect indoor concentrations. Examples of these factors are:

- Structure ventilation (eg. open vs. closed windows, operation of air-to-air heat exchangers, mechanical ventilation systems, etc.);

- Rate of soil vapor infiltration (eg. indoor stack effect from indoor/outdoor temperature differentials, mechanical devices creating negative pressure inside the structure enhancing soil vapor infiltration); and

- Rate of outdoor ambient air infiltration if a significant route of contaminant entry is from outdoor air.

By recognizing these factors, it is possible to conduct indoor testing under conditions that would result in worst case indoor concentrations. For example, if volatile organic compounds had migrated under a home and there were no significant outdoor air impacts, worst case concentrations would be expected with all outdoor air ventilation routes closed (eg. windows and doors closed, clothes dryer not operating, air-to-air heat exchanger not operating, etc.), and a large temperature differential between indoor and outdoor air creating a significant stack effect drawing in soil vapor.

Interpretation of Results - There are several ways that indoor air quality data may be examined and interpreted. There is no universally recognized protocol. These methods include comparison to established health criteria values such as Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs), and American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs). Some fraction of the health-based criteria may be used to add an extra safety factor.

4.5 EMISSIONS (PREDICTIVE) MODELING

Emissions models have been developed to predict emission rates for a variety of waste site types including landfills without internal gas generation, landfills with internal gas generation (typically co-disposal sites), open dumps, waste piles, spills, land treatment operations, aerated lagoons, non-aerated lagoons, and lagoons with an oil film. These models are almost exclusively theoretical, and each model is generally applicable to only one type of waste site.

The predictive models can be used as screening or in-depth techniques. Emissions models, used as screening techniques, employ data that can be obtained or calculated from information available in the literature, or can be assumed with some level of confidence. Emissions models, used as in-depth techniques, require site-specific site and waste characterization data. The selection of model input sources (site-specific, literature value, or assumed) should be based on the requirements of the decision-making process and the level of resources available. Site-specific data should be used whenever possible to increase the accuracy of emission rate estimates.

Several predictive models are presented below to acquaint the reader with the types of available models for emission rate estimation. The EPA's Superfund Exposure Assessment Manual (SEAMS) (41) presents simplified predictive models for many of the waste site types. The SEAMS models, simplified versions of the more complex models, are included in this section. In general, the SEAMS models are recommended for estimating emissions from the various types of uncontrolled waste sites. However, the complex models can be used if more precise estimates are required and/or more detailed site information is available.

Specific methods for calculating the model input variables, such as diffusion coefficients, have been presented by the authors of the models, but are not included here for sake of brevity. Data bases containing various input parameters are described in Appendix D. Commonly needed input data for selected compounds are listed in Appendices F and G. Each model requires estimating the emission rate of the individual components of the waste; and then summing the emission rates to determine the overall emission rate. For complex waste, application of the models is best performed on a computer to speed the calculation. An emission flux can be calculated by dividing the emission rate by the emitting area.

A wide variety of variables are associated with each of the predictive models; however, a number of key inputs are required by many of the models. These key inputs for landfills include: the vapor diffusion coefficient through the soil or mass transfer coefficient across the air/soil boundary for waste constituents; the physical size of the source expressed as area, length, and/or width, depending on the model used; physical parameters of the landfill cover, such as depth of cover, permeability, and soil porosity (total, air-filled, and/or effective porosity); physical/chemical parameters of the waste, including chemical composition, weight or mole fraction for constituents, vapor concentration of constituents at the waste surface or within the soil cover, and partial pressures of constituents; atmospheric conditions, such as temperature, wind speed and direction, and barometric pressure; and estimates of the soil gas velocity through the soil cover. The key inputs for lagoons include: mass transfer coefficients; physical/chemical parameters of the waste, including chemical composition, weight or mole fractions, partial pressures, and Henry's Law Constants; physical dimensions of the lagoon surface; atmospheric conditions, such as temperature, and wind speed and direction; layering of waste within the lagoon; and physical/ chemical parameters of a surface crust.

While all of these parameters can be estimated with varying levels of confidence, it is best, when possible, to collect site-specific data. Physical/chemical measurements of waste constituents can be obtained from sampling and analysis programs, although a records review is advisable to identify key constituents and ensure representative sampling. Likewise a sampling and analysis program combined with a records search is desirable to determine the physical size and shape of the source and the porosity and permeability of any soil cover. Atmospheric conditions are easily obtained from various weather services which can provide regional data; however, collecting some site-specific meteorologic data to ensure representativeness is desirable. Diffusion and mass transfer coefficients are typically calculated based on the wastes' chemical composition and their known chemical properties, such as Henry's Law Constants, although tabulated diffusion coefficients are now available. The referenced literature includes suggested methods for calculating the diffusion coefficients as well as some tabulated data. A list of references is given at the end of this section that contain tabulated values for selected input model parameters. Diffusion and mass transfer coefficients can also be determined experimentally in the lab; however, disturbance of the waste and landfill cover to obtain site-specific materials would probably introduce uncertainty.

4.5.1 Summary and Comparison of Emission Models

The landfill models presented here can be categorized into six types:

- Closed landfills without internal gas generation -- Farmer Model, Shen Model, SEAMS Model, Thibodeaux a Model, Logarithm Gradient Model, and RTI Closed Landfill Model;

- Closed landfills with internal gas generation -- Scholl Canyon Model, (Thibodeaux) Convective "Add-On" Model, SEAMS Model, Thibodeaux b Model, and (Thibodeaux) Exact Model;

- Open landfills -- Scholl Canyon Model, Arnold's Open Landfill Model, Shen Open Landfill Model, and RTI Open Landfill Model;

- Landtreatment -- RTI Landtreatment Model and SEAMS Model;

- Leaks and spills on soils -- SEAMS Model (Fresh Spills) and SEAMS (Old Spills); and

- Fugitive Dust -- AP-42 Vehicular Traffic, SCS Model, Cowherd Model, and Gillette Model.

The lagoon models presented in this document can be categorized into two types:

- Non-aerated lagoons -- Mackay-Lienonen; SEAMS Model; Thibodeaux, Parker, and Heck; Smith, Bomberger, and Haynes; Shen; and RTI; and

- Aerated lagoons -- Thibodeaux, Parker, and Heck; and RTI.

The applicability and characteristics of each of these models is summarized in Table 16. The complexity of the models varies depending on the number of emission mechanisms included in the model. In general, the SEAMS models are the most simplified models and have been recommended by the U.S. EPA for estimating emissions from Superfund sites (41). The SEAMS models apply to a majority of Superfund sites; however, other emission models may be more appropriate when more accurate emission estimates are required or the bases of the SEAMS models are not appropriate for a specific site. The user should consider the amount of site specific data available, the compatability of the site characteristics with the model assumptions, and the level of effort required when selecting an appropriate model.

TABLE 16. SUMMARY AND COMPARISON OF EMISSION MODELS

Waste Site/Model	Species	Soil Phase Cover	Air/Waste Interface	Liquid Phase	High Con-^{a} tration of Contaminant	Biogas Generation	Barometric Pressure Pumping	Wind	Time Func- tion	Complexity^{c} of Input Data	Comments/ Applicability	Reference Number
Closed Landfill Without Internal Gas Generation												
Farmer	VOC	X				x^{d}			SS	1	Hazardous Waste Sites	42 - 45
Shen	VOC	X				x^{d}			SS	1	Hazardous waste sites; applies to wastes with high concentration of constituent (i.e., Raoult's Law applies).	46 - 48
SEAMS	VOC	X							SS	1	Hazardous waste sites; EPA recommended.	41
Thibodeaux^{a}	VOC	X	X						SS	2	Hazardous waste sites.	45, 49
Logarithim Gradient	VOC	X			X				SS	3	Hazardous waste sites; waste concentrations >5% volume.	45
RTI Closed	VOC						X		TD	3	Hazardous waste sites; predicts long-term emissions over time.	45, 48

(Continued)

TABLE 16. (Continued)

Waste Site/Model	Species	Soil Phase Cover	Air/Waste Interface	Liquid Phase	High Con-[a] tration of Contaminant	Biogas Generation	Barometric Pressure Pumping	Wind	Time Func- tion	Complexity[c] of Input Data	Comments/ Applicability	Reference Number
Closed Landfill with Internal Gas Generation												
Scholl Canyon	VOC					X			SS/TD	1	Co-disposal sites	72
Convective "Add-on"	VOC	X				X			SS	2	Co-disposal (hazardous and municipal wastes) sites.	45
SEAMS	VOC					X			SS	1	Co-disposal sites; EPA recommended.	41
Thibodeaux[b]	VOC	X				X	X		SS	3	Co-disposal sites.	45, 49
Thibodeaux Exact	VOC	X			X	X			SS	3	Co-disposal sites.	45

(Continued)

TABLE 16. (Continued)

Waste Site/Model	Species	Soil Phase Cover	Air/Waste Interface	Liquid Phase	High Con-[a] tration of Contaminant	Biogas Generation	Barometric Pressure Pumping	Wind	Time Func- tion	Complexity[c] of Input Data	Comments/ Applicability	Reference Number
Open Landfills												
Scholl Canyon	VOC					X			SS/TD	1	Hazardous waste sites with Methane generation.	72
Arnold's Open	VOC		X						TD	2	Hazardous waste sites; diffusion from a liquid surface.	45
Shen Open	VOC		X					X	TD	2	Hazardous waste sites; accounts for wind speed.	45, 46, 47, 50
RTI Open	VOC		X					X	TD	2	Hazardous waste sites; more than one volatile constituent in liquid.	42, 45

(Continued)

TABLE 16. (Continued)

Waste Site/Model	Species	Soil Phase Cover	Air/Waste Interface	Liquid Phase	High Con-[a] tration of Contaminant	Biogas Generation	Barometric Pressure Pumping	Wind	Time Func- tion	Complexity[c] of Input Data	Comments/ Applicability	Reference Number
Land Treatment												
RTI	VOC	X						X		3	Liquid waste applied to soil surface; long-term and short-term emissions over time; biodegradation.	44, 45
SEAMS	VOC	X							TD	2	Liquid waste applied to soil surface; predicts average emission rate over time, EPA recommended.	41
Spills and Leaks on Soil												
SEAMS (Fresh Spills)	VOC		X						SS	1	Predicts emissions from visible liquid pools on soil surface; EPA recommended.	41
SEAMS (Old Spills)	VOC	X							TD	2	Predicts emissions of liquids incorporated into soil; EPA recommended.	41

(Continued)

TABLE 16. (Continued)

Waste Site/Model	Species	Soil Phase Cover	Air/Waste Interface	Liquid Phase	High Con-[a] tration of Contaminant	Biogas Generation	Barometric Pressure Pumping	Wind	Time Func-tion	Complexity[c] of Input Data	Comments/ Applicability	Reference Number
Fugitive Dust Emissions												
AP-42	Particulate								SS	2	Emissions caused by vehicular traffic on unpaved road.	54
SCS	Particulate								SS	3	Annual average emissions of wind-blown surface soils.	41
Cowherd	Particulate								SS	3	Annual average emissions of wind-blown dust from surface with a "limited" amount of erodible material.	55
Gillette	Particulate								SS	3	Emissions of wind-blown dust from surface with an "unlimited" amount of erodible material; annual and 24-hour average emissions.	55

(Continued)

TABLE 16. (Continued)

Waste Site/Model	Species	Soil Phase Cover	Air/Waste Interface	Liquid Phase	High Con-[a] tration of Contaminant	Biogas Generation	Barometric Pressure Pumping	Wind	Time Func- tion	Complexity[c] of Input Data	Comments/ Applicability	Reference Number
Non-aerated Lagoons[e]												
Mackey-Lienonen	VOC			X					TD	2	Quiescent lagoon no influx of contaminants.	56, 57
SEAMS	VOC			X						2	Quiescent lagoon constant liquid phase concentration.	41
Thibodeaux, Parker, and Heck	VOC			X					SS	3	Constant liquid phase concentration.	53
Smith, Bomberger, and Haynes	VOC			X					SS	3	Highly volatile compounds only.	37
Shen	VOC			X					SS	2	Empherical screening model.	48, 58
RTI	VOC			X					SS	2	Constant liquid phase concentration, biodegradation.	44

(Continued)

TABLE 16. (Continued)

Waste Site/Model	Species	Soil Phase Cover	Air/Waste Interface	Liquid Phase	High Concentration of Contaminant[a]	Biogas Generation	Barometric Pressure Pumping	Wind	Time Function	Complexity[c] of Input Data	Comments/ Applicability	Reference Number
Aerated Lagoons												
Thibodeaux, Parker, and Heck	VOC			X					SS	2		53
RTI	VOC			X					SS	2		44

[a] Greater than five percent by volume.

[b] SS = steady state; TD = time dependent.

[c] Scale: 1 = low complexity
2 = medium complexity
3 = high complexity

[d] Model can be used to predict emissions from landfills with internal gas generation if a multiplication factor of six is used.

[e] Can also be used to estimate emissions from contaminated water in basements and other subsurface structures.

Each general category of emission models is discussed in the following paragraphs. A detailed discussion of each model is presented in sections 4.5.2 through 4.5.10.

Closed Landfills

Most of the closed landfill models assume that the emission of volatile species is controlled by vapor diffusion through the soil cover. Additional closed landfill models have been developed to account for convective transport mechanisms which can also influence emission rates. The most significant of these convective mechanisms is biogas generation. Biogas is typically generated within co-disposal site where a mixture of municipal and solid wastes have been dumped. The upward movement (convective sweep) of the biogas within the landfill can greatly increase the upward migration of volatile species resulting in increased emissions compared to simple vapor diffusion through the soil pores. When biogas is present, it usually becomes the significant controlling factor and therefore, it is the most important consideration when selecting an appropriate landfill emission model. Other less significant convective transport mechanisms include waste concentration and atmospheric effects (i.e. barometric pressure and wind).

Waste concentrations greater than approximately 5 percent by volume can cause a convective sweep of vapor through the soil which also increases emissions. The logarithm gradient model and the Thibaodeaux exact model were developed to account for this mechanism.

Changes in barometric pressure have also been shown to have an effect on landfill emissions rates. This mechanism, referred to as barometric pressure pumping, has been incorporated into two of the landfill models (RTI closed and Thibodeaux b).

Open Landfills

The Scholl Canyon Model is a single stage, first order kinetic model that can be applied to calculate methane generation and emissions of volatile constitutents from open landfills. The Scholl Canyon Model is based on empirical factors. The model is applicable to estimating emissions over long time periods.

The other models presented for estimating emissions from the surface of open landfills are very similar to one another since the Shen Open and the RTI Open are simply modifications of the original Arnold Open Landfill model. These models are based on Fick's Second Law of unsteady-state diffusion (i.e. time dependent emission rates) and they assume that the emission rate is controlled by molecular diffusion of the volatile species through the air above the liquid surface. The models are designed for hazardous waste sites and do not apply to co-disposal sites since they do not account for increased emission rates caused by biogas generation.

The RTI model is the most complete of the models; accounting for both convective transport by wind at the waste surface and multiple species in the volatilizing liquid. One limitation of the Shen, Arnold, and RTI models is that they do not account for depletion of the volatilizing species from the surface. Because of this limitation, reviewers have judged these models to be inadequate for estimating open landfill emissions over long time periods (months or longer) (44).

Landtreatment

The landtreatment models are based of the premise that emissions from the surface are limited by vapor diffusion through the air-filled soil pores. They are applicable to sites where liquid or semi-liquid has been applied to the soil surface and become incorporated into the soil pores. The short-term version of the RTI model also accounts for convective wind losses of volatile species that can occur while liquid pools are present of the soil surface (immediately after waste application). The RTI models (short and long term) can be modified to account for biodegradation losses.

The models available for estimating emissions from landtreatment areas have been shown to produce similar results for cases where biodegradation is not important (i.e. short times and/or no soil biological activity). The SEAMS model has been recommended by the U.S. EPA for estimating landtreatment emissions; however, if biodegradation losses are significant the SEAMS model will tend to over predict emissions, particularly for longer times. Since the RTI model accounts for losses due to biodegradation it is more useful for estimating long term emissions. For short times, both models will produce similar results.

Spills and Leaks on Soil

The U.S. EPA's Superfund Exposure Assessment Manual (SEAMS) recommends the two models listed in Table AA for estimating emissions from fresh and old spills on soil. The model for fresh spills is applicable when a contaminant pool is visible on the soil surface or when the soil is saturated from the surface down. The model does not consider diffusion through the soil phase and therefore does not apply to cases where contaminants have seeped into surface soils. In this case, the SEAMS model for old spills (equivalent to the SEAMS model for landtreatment) is recommended for estimating emissions of volatile species.

Lagoons

Models are available for predicting emission from two types of lagoons; non-aerated (quiescent) lagoons and aerated (turbulent) lagoons. Since most abandoned hazardous waste lagoons will probably be inactive, the model equations for non-aerated lagoons will apply in most cases. The models for aerated lagoons are simply modified versions of the non-aerated models and are presented here for completeness.

The SEAMS model for non-aerated lagoons, recommended by the U.S. EPA, is a simplified steady-state version of the of the Mackay-Leinonen model and is based on the following assumptions: (1) a constant concentration of contaminant in the liquid phase (i.e. no input of contaminant to the lagoon); and (2) negligible atmospheric background levels of the volatile contaminant.

The SEAMS model is a valid estimation technique for lagoons which meet these conditions. However, the liquid phase concentration will decrease over time if there is not a constant influx of contaminant to the lagoon to maintain the concentration. Under these conditions, the SEAMS model will tend to overpredict emissions; the unsteady-state Mackay-Leinonen model is more appropriate since it is designed to account for a depletion of the contaminant in the liquid phase over time.

The models developed by Thibodeaux, Parker, and Heck , and RTI are very similar to the SEAMS model for the case of non-aerated lagoons. These models can also be modified to estimate emission from aerated lagoons. The RTI model has also been designed to account for biodegradation losses.

Other models are less useful because of uncertainties associated with input data or model applicability. The Smith, Bomberger, and Haynes model is only applicable for emissions prediction for highly volatile compounds. In addition, representative values for some input parameters are difficult to obtain. The model developed by Shen is an empirical relationship that is applicable as a screening technique to determine if lagoon emissions may be significant.

Fugitive Dust

The models presented here are useful for predicting fugitive dust (particulate) emissions from contaminated soil surfaces. Two types of models are available: (1) those that predict emissions caused by vehicular traffic on contaminated unpaved roads (AP-42 model); and (2) those that predict wind blown dust emissions (SCS, Cowherd and Gillette models). All of the models are designed or can be modified to estimate respirable (less than 10 um diameter) and non-respirable (greater than 10 um diameter) fractions.

The models for predicting wind-blown dust emissions are similar; however, there are some minor differences. The SCS model and the Cowherd model are designed to predict annual average emissions, whereas the Gillette models can be used to predict annual and 24-hour worst case emissions. In addition, the models developed by Cowherd and Gillette are applicable to surfaces with limited erodibility and unlimited erodibility, respectively. The wind erosion potential of the surface, which is a function of vegetation cover and number of nonerodible elements such as stones, must be characterized before an appropriate model can be chosen.

4.5.2 Emission Models for Closed Landfills without Internal Gas Generation

Farmer Model--

The Farmer Model (42-45) was one of the first models developed and generally accepted to predict emission rates from covered landfills. The rate at which a compound is lost to the atmosphere from the land surface is controlled by the compound's molecular diffusion through the soil covering the waste. Farmer et al. developed this model to determine hexachlorobenzene vapor diffusion through a soil cover. They found that the two prime factors controlling/determining vapor movement through the soil were soil depth and soil air-filled porosity. The model should be applicable to other compounds as well.

The Farmer Model combined Fick's First Laws for steady-state diffusion with the Millington and Quirk evaluation of the diffusion coefficient. The latter included a porosity term accounting for the soil's geometric effects on diffusion for a given compound.

The Farmer equation is (43):

$$J = D_1(C_1 - C_S)(P_a^{10/3}/P_T^{2})/L \qquad \text{(Eq. 15)}$$

where J = volatilization vapor flux through the soil cover (ug/cm^2-day);

D_1 = vapor diffusion coefficient in air (cm^2/day);

P_a = air-filled soil porosity (cm^3/cm^3);

P_T = total soil porosity (cm^3/cm^3);

C_S = concentration of volatilizing material at the surface of soil layer (ug/cm^3);

C_1 = concentration of the volatilizing material at the bottom of the soil layer (ug/cm^3); and

L = depth of the soil layer (cm).

Farmer et al. simplified the equation somewhat by assuming a worst-case scenario, where the soil is completely dry (P_a equals P_T) and where the concentration at the surface (C_2) equals 0, meaning any increase in C_2 would effectively reduce the driving force behind the vapor flux and, thus, reduce the vapor flux from the soil surface. Farmer et al. called this equation the Assessment Application (43):

$$J = D_1 P_T^{4/3} C_S / L \qquad \text{(Eq. 16)}$$

Applicability--

The Farmer Model provides an estimate of individual compound emissions. The intended applicability of the Farmer Model is quantification of steady-state volatile chemical fluxes from hazardous waste landfills. This model does not account for convective transport due to biogas generation and is not applicable to municipal landfills or other landfills containing gas generating wastes. Use of the Farmer Model assumes the transport of a volatile compound through the soil cover layer is controlled by a molecular diffusion process.

Limitations--

The Farmer Model assumes that the soil/waste below the soil cover layer is saturated with constituent i. This assumption tends to overestimate the emissions by not accounting for the true concentration gradient below the soil cover. Additionally, the Farmer Model does not account for the emissions associated with atmospheric/meteorological effects such as barometric pressure fluctuations. Also, at high concentrations (greater than 5 percent by volume), the diffusion process creates its own convective sweep or apparent velocity within the landfill. This convective mechanism is not accounted for by the Farmer Model (59). These latter two limitations are likely to result in underestimates of landfill emission rates.

Shen Model--

Shen modified the Farmer Model (46-48) to determine a vapor emission rate, as opposed to the vapor flux rate, and to enable calculation of the volatilization of specific components of the complete waste mixture. This modification assumes Raoult's Law applies. Shen multiplied the Farmer equation by the exposed contaminated surface area and by the weight fraction of the component in the mixture. The modified equation is (46):

$$E_i = D_i C_i A (P_t^{4/3}) \frac{W_i}{L\,W} \qquad \text{(Eq. 17)}$$

where E_i = emission rate of the component i (g/sec);
D_i = diffusion coefficient of component in air (cm^2/sec);
C_i = saturation vapor concentration of component i (g/cm^3);
A = exposed area (cm^2);
P_t = total soil porosity (dimensionless);
L = effective depth of the soil cover (cm); and
W_i/W = weight faction of component i in the waste (g/g).

The model assumes completely dry soil and zero concentration of volatilizing material at the soil surface, a worst-case scenario considered appropriate for cap design and most analyses for volatilization release from landfill wastes. This assumption should be used in all cases except where cover soils can be shown to have significant soil moisture. In these instances, the soil air-filled porosity should be substituted into the equation for the total porosity by replacing $P_t^{4/3}$ with $P_a^{10/3}/P_T^2$.

Applicability--

The Shen Model differs from the Farmer Model in that it relates emissions to the waste composition with a weight factor (wi) and multiplication of the flux by the landfill area. Like the Farmer Model, the intended applicability is quantification of steady-state volatile chemical emission rates from hazardous waste landfills. This model does not account for convective transport due to biogas generation and is not applicable to municipal landfills or other landfills containing gas generating wastes. In the use of the Shen Model, it is assumed that the relatively toxic properties of organic waste placed in hazardous and industrial waste landfills minimize gas production due to biodegradation.

Limitations--

The Shen Model does not account for the landfill gas losses in leachate systems, run off, or soils. But here again, due to the inert properties of the volatile constituents, this accountability is considered by Dr. Shen to be minute. The Shen Model also assumes that the soil is completely dry with no internal gas generation. However, the Shen Model can be modified to account for biogas generation with a multiplicative factor of 6. This assumption would tend to overestimate emissions by not accounting for actual wet soil conditions below the soil cover layer. As with the Farmer Model, the Shen Model does not account for emissions due to meteorological fluctuations (e.g., barometric pressure pumping).

Another limitation of the Shen Model is the incorporation of Raoult's Law to relate the waste composition to emission rate. Raoult's Law is applicable only to waste saturated with constituent i and ideal solutions. Application of the Shen Model to wastes containing dilute concentrations of the constituent i is likely to result in an overestimate of emission rate.

SEAMS Model--

The model recommended in the U.S. Environmental Protection Agency's SEAMS manual is a slightly modified version of the Shen Model (41). This modified model was proposed by Farino et.al. (49) who found that a more accurate approach would be to multiply by the mole fraction of the volatile component in the buried mixture.

$$E_i = D_i C_i A \left(P_t^{4/3}\right) \frac{M_i}{L} \qquad \text{(Eq. 18)}$$

where: E_i = emission rate of the component i (g/sec);

D_i = diffusion coefficient of component in air (cm^2/sec);

C_i = saturated vapor concentration of component i (g/cm^3);

A = exposed area (cm^2);

P_t = total soil porosity (dimensionless);

L = effective depth of soil cover (cm); and

M_i = mole fraction of component i in the waste (gmole/gmole).

The SEAMS manual provides guidance on methods for estimating or calculate values for the model input parameters (41).

Applicability--

The SEAMS model applies to the same situations described for the Shen model.

Limitations--

The SEAMS model and Shen model have similar limitations; however, the SEAMS model relates the waste composition to the emission rate more accurately.

Thibodeaux a Model--

The Thibodeaux a Model (45,49) was developed by Thibodeaux to estimate the emissions of volatile constituents due to interphase vapor transport from landfills with no internal gas generation. The model is derived from Fick's Law of steady state diffusion. Molecular diffusion is the controlling and only transport mechanism addressed by the Thibodeaux a Model for the movement of volatile constituents toward the soil/air interface and then to the overlying air. To describe this mechanism, the two-resistance theory is used to describe the two-film resistance in which the movement of chemical constituents is limited by their ability to diffuse through the soil and after migration from the surface, through the air.

The model assumes that a pure component i exerts its pure component vapor pressure under the earth, subject to normal geophysical and meteorological factors. Thibodeaux defines an overall mass transfer coefficient to describe vapor movement which is hindered by both the resistance due to soil characteristics and diffusion resistances at the air interface.

$$E_i = {}^1K_i\ (C_i - C_{ii})\ A \qquad \text{(Eq. 19)}$$

$$E_i = E_{soil} + E_{air/soil} \qquad \text{(Eq. 20)}$$

where ${}^1K_i$ = overall soil phase mass-transfer coefficient (cm/sec);
C_{i1} = concentration of i above the soil/air interface (g/cm^3);
C_i = concentration of i in the sand-filled chamber pore spaces (g/cm^3);
Ei = rate of vapor movement within the soil phase (g/sec); and
A = landfill surface area (cm^2).

$$E_{soil} = \frac{{}^1D_E}{L}(C_i - C_s)A \qquad \text{(Eq. 21)}$$

where ${}^1D_E$ = effective diffusivity of constituent i within the pore spaces (cm/sec);
L = depth of the soil fill cover (cm); and
C_s = concentration of i at the air/soil interface (g/cm^3).

$$E_{air/soil} = {}^3D_i\ (C_s - C_{i1})\ A \qquad \text{(Eq. 22)}$$

where ${}^3D_i$ = gas phase mass-transfer coefficient using the equation developed by MacKay and Matsugu (m/hr).

$${}^3D_i = 0.0292\ V_x^{0.78}\ L_x^{-0.11}\ S_c^{-0.67} \qquad \text{(Eq. 23)}$$

where: V_x = wind speed measured at 10 m (m/hr);
L_x = length of the ground emission source in the direction of the wind (m); and
S_c = Schmidt number for the gas.

Overall mass-transfer coefficient:

$$\frac{1}{{}^1K_i} = \frac{1}{{}^1D_i} + \frac{1}{{}^3D_i} \qquad \text{(Eq. 24)}$$

where ${}^1D_i = D_i\epsilon/\tau_h$
τ_h = tortuosity, taken to be 3
ϵ = porosity of the cover material

Applicability--

Like the Farmer and Shen models, the intended application of the Thibodeaux a Model is a hazardous waste landfill. This model does not account for convective transport due to internal gas generation typically present in municipal landfills.

Limitations--

The Thibodeaux a Model does not account for the possible emissions due to barometric pressure fluctuations or internal gas generation. In addition, the Thibodeaux a Model does not account for the convective sweep of a volatile constituent caused by high concentrations greater than 5 percent by volume. A number of factors, such as waste composition, multicomponent systems, and biological or chemical reactions, greatly increase the uncertainty in the use of the two-resistance theory.

Logarithm Gradient Model--

The Logarithm Gradient Model (45) is the modern day interpretation of the Farmer Model developed to address volatile constituent emission rates for landfill concentrations greater than 5 percent by volume. In general, this model takes into account both the diffusive mechanism as described by Fick's Law and the convective mechanism due to the sweep or apparent velocity which diffusion can create with high concentrations.

The Logarithm Gradient Model is (45):

$$E_i = D_E \, P_T \, \frac{M}{RTL} \, \mathrm{Ln} \left[\frac{P_T - P_i}{P_T - P_i^*} \right] A \qquad \text{(Eq. 25)}$$

where E_i = emission rate (g/sec);
D_E = effective diffusion coefficient (cm^2/sec);
P_T = total pressure below the cover layer (mm Hg);
M = mole weight of constituent (g/mol);
R = molar gas constant (cm^3 mm Hg/mol °K);
T = absolute temperature (°K);
L = length of soil cover (cm);
P_i = partial pressure at the air-soil surface (mm Hg);
P_i^* = partial pressure of the volatilizing material in soil gas at the bottom of the soil depth (mm Hg); and
A = landfill surface area (cm^2).

Applicability--

This model can generally be applied to landfill situations where molecular diffusion is the controlling vapor transport mechanism. The model accounts for the apparent velocities associated with high volatile concentrations, but does not account for the convective sweep movement associated with co-disposal (biogenic gas production) practices.

Limitations--

The limitations indicated for both the Farmer Model and the Shen model apply to this model. However, the Logarithm Gradient Model accounts for convective transport resulting from the diffusion of highly volatile constituents (greater than 5 percent by volume).

RTI Closed Landfill Model--

The Research Triangle Institute (RTI) closed landfill model (45,48) accounts for emissions via two mechanisms: diffusion through the soil cap and convective loss from barometric pumping through passive landfill vents. The model is based on the Farmer Model (above) which was modified to account for convective losses due to barometric pumping and the decline in emission rate over time.

The total instantaneous emission rate is a function of the total initial emission rate at the time of landfill closure which is the sum of the instantaneous emissions associated with diffusion through the cap and barometric pumping.

(Eq. 26)

$$E_i^* = E_{1i} + E_{2i}$$

where E_i = total initial emission rate at the time of closure (g/sec);

E_{1i} = emissions associated with diffusion through the cap (g/sec); and

E_{2i} = emissions associated with barometric pumping (g/sec).

The equations for estimating E_{1i} and E_{2i} are present below.

$$E_{1i} = \frac{AD_i}{L} \left[P_A^{10/3} / P_T^2 \right] (C_i - C_s) \qquad \text{(Eq. 27)}$$

where A = landfill surface area (cm^2);

D_i = vapor diffusion coefficient in air (cm^2/sec);

P_A = soil cap air-filled porosity (cm^3/cm^3);

P_T = total porosity of the soil cap (cm^3/cm^3);

C_i = concentration of constituent in the vapor space beneath the cap (g/cm^3);

C_s = concentration of constituent in the air above the cap (g/cm^3) assumed to be 0; and

L = cap thickness (cm).

$$E_{2i} = Q\, C_i\, A \qquad \text{(Eq. 28)}$$

where Q = flow rate of gas through the vent (cm^3/cm^2-sec);
C_i = concentration of constituent in the gas within the landfill (g/cm^3); and
A = landfill surface area (cm^2).

$$Q = \left[hA\, E_{fw} \left[\frac{P_r}{P_1} \right] \left[\frac{T_1+273}{T_r+273} \right] -1 \right] \qquad (\Delta t\, A) \qquad \text{(Eq. 29)}$$

where h = thickness of waste bed within landfill (cm);
E_{fw} = air porosity fraction of fixed wastes;
P_r = reference barometric pressure (mm Hg);
P_1 = final barometric pressure (mm ug);
T_r = reference landfill temperature (°C);
T_1 = final landfill temperature (°C); and
Δt = time interval over which change in pressure and/or temperature occurred (sec).

The total instantaneous emission rate at any time is then computed via an exponential decay function:

$$E_i(t) = 31.56\, \overset{*}{E_i} \exp(-\lambda t) \qquad \text{(Eq. 30)}$$

where $E_i(t)$= total time-dependent emission rate (mg/yr);
$\overset{*}{E_i}$ = initial emission rate, at time of landfill closure (g/sec);
t = time since landfill closure (mo); and
λ = decay constant (mo^{-1}) = 2.63 x 106 $E_i{}^*/M_{oi}$; and
M_{oi} = total mass of the constituent in the landfill (g).

The average emission rate from a closed, vented landfill over the time since landfill closure is given by the following expression:

$$E_{A_i}(t) = \frac{2.63\, E}{\lambda}\, i\, [1-\exp(-\lambda t)] \qquad \text{(Eq. 31)}$$

where $E_{Ai}(t)$ = average emission rate over the time since landfill closure (mg/yr);

t = time since landfill closure (mo);

λ = decay constant (mo^{-1}); and

$\overset{*}{E}_i$ = initial emission rate at time of landfill closure (g/sec).

The RTI closed landfill model assumes that no biodegradation occurs and that the landfill is passively vented to the atmosphere. Transport of the constituent in moving water is assumed not to occur.

Applicability--

The RTI Model estimates the time-dependent behavior of emissions from landfills. RTI modified the Farmer Model to account for the convective loses from barometric pumping through vents. In addition, the RTI Model was designed to account for the decline in the emission rate from closed landfills over an extended period of time. The time dependency was incorporated simply by adding an exponential decay function. The decay constant was taken as the ratio of the emission rate at the time of landfill closure to the total mass of the constituent in the landfill.

Limitations--

The RTI Model does not include convective or purging action associated with biogas production commonly found at municipal solid waste landfills. It assumes, as did the Shen and Farmer models, that the toxic properties of the waste will inhibit biological processes and, thus, prevent biogas generation. Furthermore, the liquid waste which contains the volatile constituent i is assumed to be bound in the fixed waste within the landfill cell. No experimental or field verification has taken place.

4.5.3 Emission Models for Closed Landfills with Internal Gas Generation

The Scholl Canyon Model--

The Scholl Canyon Model was developed by Emcon Associates and Jacobs Engineering Company as part of a feasibility study of the recovery of methane from the Scholl Canyon Sanitary Landfill in aliformia. The model is a single-stage, first-order kinetic model which assumes that after a lag time of negligible duration, during which anaerobic conditions are established and the microbial biomass is built up and stabilized, the production rate of meathane is at its peak. The gas production is then assumed to decrease as the organic fraction of the landfill decreases. The Scholl Canyon Model is:

$$Q_{CH4} = k \, L_O \, \Sigma \, M_I \, {}^{\;n}_{i=1} \, \exp(-k_{ti}) \qquad \text{(Eq. 32)}$$

where Q_{CH4} = methane flowrate m^3/yr.
k = methane generation rate constant 1/yr.
L_O = potential methane generation of refuse, m^3/Mg of refuse.
M_I = mass of submass i, Mg.
t_i = year since the initial placement for submass i, yr.
n = number of submasses in the landfill.

The total methane generation from the entire landfill is at its peak upon landfill closure. If a constant annual acceptance rate is assumed, the form of the model can be simplified to:

$$Q_{CH4} = L_O \, R \, [\exp(-kc) - \exp(k-t)] \qquad \text{(Eq. 33)}$$

where R = average annual acceptance rate of refuse, Mg/yr
c = the time since landfill closure.

A lag time during which anaerobic conditions are established can be incorporated into the model by substituting (c + lag time) for c and (t + lag time) for t. Typical lag times range from 200 days to several years depending on landfill conditions.

The emission of volatile constituents can be calculated as a function of the methane generation rate.

$$Q_c = (Q_{CH4})\ 2\ (C_c) \qquad \text{(Eq. 34)}$$

where Q_c = Volatile constituent emission rate, m^3/yr.

2 = multiplication factor (assuming landfill gas consists of 50% methane and 50% carbon dioxide).

C_c = volatile constituent initial concentration within the landfill 10^{-6} ppmv.

Q_{CH4} = methane flowrate, m^3/yr.

Applicability--

The Scholl Canyon Model can be used to estimate emissions from closed landfills with internal gas generation assuming that all the gas that is generated is emitted. The mass emission rate can be computed by using the ideal gas law to convert from volumetric flowrate. This model was selected for use for the Clean Air Act Regulations for municipal solid waste landfills which are to be proposed in the Fall of 1990.

Limitations--

The model assumes no lateral migration of emitted gases takes place. No verification of a kinetic model using field data from landfills to describe the time dependency of gas production has been performed. This is the case for most, or all, of the models discussed in this document. EPA's Air and Engineering Research Laboratory is conducting work to field validate gas production models for the global climate change program.

(Thibodeaux) Convective "Add On" Model--

The Convective "Add On" Model was developed by Thibodeaux to account for both the diffusion and convective mechanisms present in landfills at which co-disposal of municipal solid waste and hazardous organic waste has been practiced. The model describes the migration of a chemical constituent i due to the convective gas sweep of biological gas production within the soil cover layer. As the apparent velocity, Vy, of the constituent, approaches zero, the model reduces to the diffusion controlled Farmer Model described above.

The Convective "Add On" Model is (45):

$$E_i = \frac{V_y \ (C_i - C_s)}{[\exp \ (LV_y/D_E)-1]} + V_y C_i A \qquad \text{(Eq. 35)}$$

where E_i = rate of vapor movement within the soil phase (g/sec);
V_y = mean gas velocity in pore spaces (cm/sec);
C_i = concentration of i in sand chamber filled pore spaces (g/cm^3);
C_s = concentration of i at the air-soil interface (g/cm^3);
L = depth of fill cover (cm);
D_E = effective diffusivity of i within the soil pore space (cm^2/sec); and
A = landfill surface area (cm^2).

Applicability--

The Convective "Add On" Model can be used to estimate volatile emissions from landfills with internal gas generation. This model accounts for both diffusion and convective transfer. However, the transfer due to net upward gas flow greatly overshadows the diffusion transfer mechanism (59). This deduction is based, in part, on laboratory experiments of simulated gas flow through a soil cover.

Limitations--

A major limitation of this model is the required input of mean gas velocity through the soil cover. The limitations applied to the Farmer and Shen Models apply to this model as well. However, the "Add On" Model does account for biogas convection.

SEAMS Model--

The model recommended in the SEAMS manual for landfills with internal gas generation is a simplified version of the Convective "Add-On" model. This model assumes that the effect of biogas generation are so great that soil and gas phase diffusion becomes insignificant. The simplified model is (41):

$$E_i = C_i V_y A \qquad \text{(Eq. 36)}$$

where
E_i = emission rate of component i (g/sec);
C_i = concentration of component in the soil pore spaces (g/cm^3);
V_y = mean landfill gas velocity in the soil pores (cm/sec); and
A = landfill surface area (cm^2).

This model was shown to produce emission rates within one percent of the values obtained using the Convective "Add-On" model. The SEAMS manual provides guidance on estimating values for model parameters.

Applicability--

The model is recommended by EPA-Superfund for estimating volatile emissions from landfills with internal gas generation.

Limitations--

This model is limited by the accuracy of the values used for the mean gas velocity. A representative value for this parameter may be difficult to obtainf or a specific site; however, Thibodeaux provides an average value of 1.63×10^{-3} cm/sec. The accuracy of this model for estimating emissions from landfills with moist or wet soils is unknown.

Thibodeaux b Model--

The Thibodeaux b Model (45,49) includes emissions due to barometric pressure pumping. The model accounts for the air emissions resulting from concentration gradients (diffusion), biogas generation sweeps (convection), and barometric pressure pumping (convection) (51). The barometric pressure fluctuations create a pressure gradient within the landfill cell, pumping vapors to the atmosphere.

The Thibodeaux b Model incorporates Darcy's Law to characterize the laminar flow of gases flowing through porous media due to pressure gradients. The gas flow velocity within the landfill cell can be estimated as:

$$V = (k\rho g/uL)(P-\rho) = (Kg/L)(P-\pi) \qquad \text{(Eq. 37)}$$

where V = velocity;

k = specific permeability of covering material in Darcys or cm2;

u = viscosity of gas;

ρ = density of gas;

L = soil cover thickness;

P = landfill cell pressure;

π = barometric pressure;

g = acceleration of gravity; and

K = permeability (cm/sec).

The Thibodeaux b Model is (45):

$$E_i = \frac{D_E}{L} \; C_i \; \frac{R \exp R}{\exp R-1} \; A \qquad \text{(Eq. 38)}$$

where $R = \dfrac{LV}{D_E}$ (Eq. 39)

$$V = \frac{k}{uL}(P-\pi) \qquad \text{(Eq. 40)}$$

E_i = emission rate (g/sec);

C_i = concentration of i in the sand chamber filled pore spaces (g/cm^3);

V = superficial velocity through the soil cover layer (cm/sec);

k = permeability of soil cover layer material (cm^2 cp/sec atm);

P = landfill cell pressure (atm);

u = landfill cell gas viscosity (cp);

π = atmospheric pressure (atm);

L = depth of soil cover layer (cm);

D_E = effective diffusivity of i within the air-filled soil pore space (cm^2/sec); and

A = landfill surface area (cm^2).

Applicability--

The Thibodeaux b Model can be applied to situations where molecular diffusion, convection, and barometric pressure fluctuations are to be expected. Efforts by Springer indicate that the annual barometric pressure fluctuation does not average out to one and, therefore, should be considered. Furthermore, Springer observed through computer simulations of flux with benzene that barometric pressure fluctuation only slightly influenced the flux rate at co-disposal facilities, and greatly influenced the flux rate at hazardous waste landfills where no internal gas generation is expected.

Limitations--

The limitations observed in Thibodeaux's Convective "Add On" Model applied to this model with the exception of barometric pressure fluctuations. Springer's observations indicate that the Thibodeaux b Model is applicable to landfills with no internal gas generation (51).

Exact Model--

The Exact Model, (45) developed by Thibodeaux, is a steady state model which accounts for diffusion due to concentration gradients, the convective velocity created by highly volatile compounds, and convection due to biogas generation (50). Application of the model requires an iterative procedure, since the flux term, Ji, appears on both sides of the equation. The Logarithm Gradient Model discussed above is used to calculate the initial estimation of the flux to start the iterative calculation. Since it is a steady-state model, the flux is not given as a function of time and the concentration of constituent i is assumed to be constant within the landfill cell.

The Exact Model is (45):

$$J = \frac{VP_A M_A}{RT} \left[1 - \frac{P_A}{P_T} - \exp \left[- \left[\frac{Ji}{M_A} + \frac{VP_T}{RT} \right] LRT/P_T D \right] \right] \quad \text{(Eq. 41)}$$

where J_i = volatile chemical flux (g/cm^2-sec);
V = apparent biogas velocity (cm^3/cm^2-sec);
P_A = vapor pressure of chemical A (atm);
M_A = molecular weight of chemical A (g/mole);
P_T = atmospheric pressure (atm);
L = soil layer thickness (cm);
D = effective diffusion coefficient (cm^2/sec);
$D = (EN)\ D_{A1}\ e_a^{10/3}/e^2$;
EN = enhancement factor from experimental data;
D_{A1} = diffusion coefficient of chemical A in air;
e = porosity of soil layer;
e_a = air-filled porosity of soil layer;
R = molar gas constant; and
T = absolute temperature (°K).

Applicability--

The intended applicability of this model is municipal landfills with internal gas generation. This model can be used to estimate the flux of a volatile constituent i from closed landfills due to both diffusion and convective transport mechanisms. However, this model can only be used for landfills with an internal gas velocity greater than zero.

Limitations--

When the model predictions were compared to the experimental data developed by Thibodeaux, large discrepancies were observed. The experimental emission rates were higher than the model predictions, and Thibodeaux attributes this deviation to surface diffusion which occurs in parallel with pore diffusion and, in general, enhances the total diffusion rate.

Thibodeaux incorporates the enhancement factor, EN, in the Exact Model to account for the discrepancies observed between the effective diffusivity (obtained by laboratory experiments) and the Millington-Quirk diffusivity. Therefore, one major limitation of Thibodeaux's Exact Model is the availability and accuracy of the enhancement factor. Another limitation of Thibodeaux's Exact Model is that the value of the apparent gas velocity, V, needs to be known. In order to apply Thibodeaux's Exact Model, the enhancement factor needs to be experimentally obtained for the specific constituent, soil type, soil cover depth, gas type, gas velocity, and gas humidity.

Thibodeaux's Exact Model may be useful in estimating the order of magnitude value of the emission flux if the soil cover depth is less than 10 cm. The enhancement factor for a shallow soil cover (i.e., 7.62 cm) ranges from 1.58 to 4.93 compared to the range of 5.54 to 17.2 for a deep soil cover layer (i.e., 38.1 cm).

4.5.4 Emission Models for Open Landfills

Emission Models for Open Landfills The Scholl Canyon Model--

The Scholl Canyon Model, a single stage, first order kinetic model, can be applied to calculate methane generation within an open landfill. For open landfills it has the following form:

$$Q_{CH4} = k\, L_0 \sum_{i=1}^{n} M_I \quad \exp(-k_{ti}) \qquad \text{(Eq. 42)}$$

where Q_{CH4} = methane flowrate m^3/yr
k = methane generation rate constant, 1/yr
L_0 = potential methane generation of refuse, m^3/Mg of refuse
M_i = mass of submass i, Mg
t_i = year since the initial placement for submass i, yr
n = number of submasses in the landfill

A simplified form of the equation can be used if a constant annual acceptance rate is assume. This is the form of the simplified model:

$$Q_{CH4} = L_0 R [1\text{-exp} (kt)] \qquad \text{(Eq. 43)}$$

where R = average annual acceptance rate of refuse, Mg/yr

A lag time during which anaerobic conditions are established can be incorporated into the model by substituting (c + lag time) for c and (t + lag time) for t. Typical lag time range from 200 days to several years depending on landfill conditions.

The emissions of volatile constituents can be calculated as a function of the methane generation rate.

$$Q_c = (Q_{CH4})\ 2\ (C_c) \qquad \text{(Eq. 44)}$$

where Q_c = Volatile constituent emission rate, m^3/yr
2 = multiplication factor (assuming landfill gas consists of 50% methane and 50% carbon dioxide).
C_c = Volatile constituent initial concentration within the landfill 10^{-6}, ppmv.
Q_{CH4} = methane flowrate m^3/yr.

Applicability--

The Scholl Canyon Model can be used to estimate emissions from open landfills assuming that all the gas that is generated is emitted. The mass emission rate can be computed by using the ideal gas to convert from volumetric flow rate.

Limitations--

There are no available field data from landfills which will allow verfication of a kinetic model to describe the time dependency of gas production.

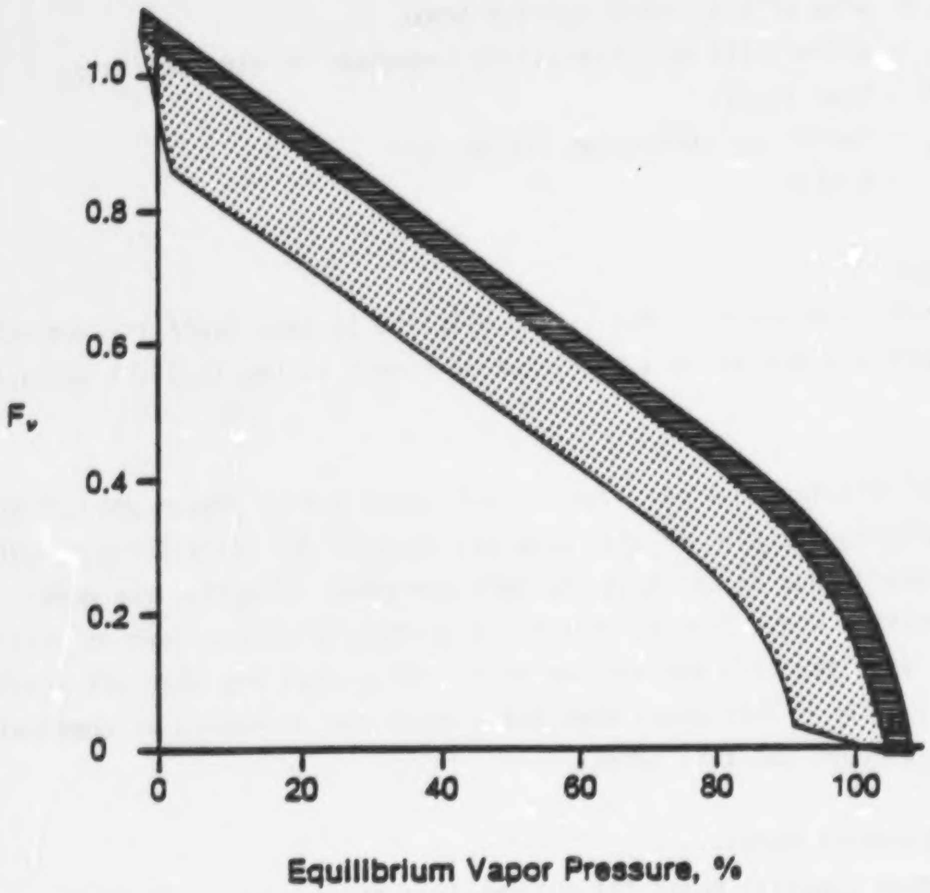
Arnold's Open Landfill Model--

The Arnold Open Landfill Model (45) provides an estimate of the cumulative vapor release from the surface of open landfills as a function of time. Arnold's Open Landfill Model applies Fick's Second Law of unsteady-state diffusion to describe the diffusion process from a liquid surface at which the concentration of volatilizing liquid remains constant. The model assumes that the air space above the liquid surface is at a constant pressure and convective forces are absent.

In applying Fick's Second Law, Arnold incorporated a correction factor for Fick's Second Law to account for the displacement of the air (or inert gas medium) by the volatilizing constituent. This correction factor is a function of the equilibrium vapor pressure of the constituent. Values of Fick's correction factor, Fv, are plotted against equivalent vapor pressure in Figure 21.

The Arnold Open Landfill Model is (45):

$$V^o = 2y^* A \sqrt{\frac{D_i t}{\pi F_V}} \qquad \text{(Eq. 45)}$$



Reference: Shen, T.T., "Estimating Hazardous Air Emissions from Disposal Sites." Pollution Engineering, August, 1981.

Figure 21. Fick's correction factor, Fv, plotted against equilibrium mole fraction, y^*.

where V^o = volume of vapor released at ambient pressure and temperature (cm^3);

y^* = equilibrium mole fraction of the volatilizing component in the gas phase at the liquid-gas interface;

A = area of the liquid surface (cm);

D_i = diffusivity of volatilizing component in air (cm2/sec);

t = time (sec);

F_v = Fick's Law correction factor; and

π = 3.1416

Applicability--

The Arnold Open Landfill Model is applicable to open landfills and dumps where emissions are due to volatilization of liquid at the landfill surface.

Limitations--

The model assumes that emissions do not occur due to biogas production or barometric pumping. The model also does not account for the effects of wind speed which would tend to increase the emission rate. Finally, the model assumes a constant waste source, whereas, a surface crust may form as volatile constituents are lost from the surface soil. This crust may then act similar to a landfill cover. This model does not account for transport of chemicals by diffusion through the soil pores.

Shen's Open Landfill Model--

Shen's Open Landfill Model (44,45) provides the average volumetric emission rate of the volatile constituent from open landfill surfaces. Shen modified the Arnold Open Landfill Model to account for the convection due to wind speed. Shen took the time derivative of the Arnold Model and changed the time function, t, in the model to a position function. This position function is related to the length of the open dump and the wind speed.

The Shen Open Landfill Model is:

$$\frac{dV_i}{dt}_{avg} = 2_y{}^{*} W_L \sqrt{\frac{D_i L_L U}{\pi F_V}} \qquad \text{(Eq. 46)}$$

where $\frac{dV_i}{dt_{avg}}$ = average emission rate (cm /sec^3);

y_i^{*} = equilibrium mole fraction;
W_L = width of open landfill (cm);
D_i = diffusion coefficient (cm2/sec);
U = wind speed (cm/sec);
F_V = Fick's law correction factor;
L_L = length of open landfill (cm); and
π = 3.1416

The model has also been presented as Ziegler's modification of Arnold as (46,50):

$$\frac{dV}{dt} = 2\ CeW\ (DLv/\pi FY)^{1/2} Wi \qquad \text{(Eq. 47)}$$

where $\frac{dV}{dt}$ = emission rate;
W = width of landfill;
L = longest dimension of the landfill;
v = wind speed;
Wi = weight fraction of a specific compound in the waste;
Ce = equilibrium vapor concentration;
D = diffusion coefficient; and
FY = correction factor.

The emission rate can increase with increasing wind speed; however, the dilution fraction also increases. The net effect of wind speed on ambient concentration, therefore, becomes compensative and depends on receptor location.

Applicability--

The Shen Open Landfill Model is applicable to open landfills where emissions are due to volatilization at the landfill surface. It appears that this model is useful as a screening process to examine whether volatilization will be significant for a given contaminant (47).

Limitations--

The model does not provide for biogas generation or barometric pumping. The model also does not provide for the formation of a weathered surface which would tend to reduce emissions similar to a closed landfill cover.

RTI Open Landfill Model--

Research Triangle Institute (RTI) modified the Shen Open Landfill Model by introducing the mole fraction of the constituent to account for more than one volatile constituent in the liquid. The RTI Open Landfill Model, shown below, uses the ideal gas law to convert the volumetric emission of the Shen Open Landfill Model and provide an average mass emission rate.

The RTI Open Landfill Model is (42,43):

$$E_i = \frac{2PM_iY_i^* W_L}{RT} \quad \frac{D_iL_L U}{\pi F_V} \qquad \text{(Eq. 48)}$$

where E_i = average mass emission rate of component i (g/sec);
P = ambient pressure (mm Hg);
M_i = molecular weight of component i;
Y_i^* = equilibrium mole fraction of component i in the gas phase;
W_L = width of open landfill;
D_i = diffusivity of component i in air (cm^2/sec);
L_L = length of open landfill (cm);
U = wind speed (cm/sec); and
F_V = Fick's Law correction factor.

Applicability--

The RTI Open Landfill Model is applicable to open landfills where emissions are due to volatilization at the landfill surface.

Limitations--

The model does not account for biogas production, barometric pumping, or formation of a surface crust. The model does not account for depletion of the volatiizing chemical from the waste surface; thus, it is not applicable for estimating emissions over long time periods (i.e., months).

4.5.5 Emission Models for Landtreatment

RTI Land Treatment Model--

Research Triangle Institute (RTI) has developed a model (44,45) for estimating emissions from land treatment areas. The model is comprised of two equations; one for short time (immediately after application or tilling) and one for longer times. The RTI land treatment equations are based on the premise that emissions are limited by vapor diffusion through the soil. The model accounts for the removal of organic material from the land treatment area by both biological degradation and air emissions.

The expression for the instantaneous emission rate for short time periods immediately following initial waste deposition is given by:

$$E_i = \frac{M_o}{l}\left[\frac{1}{\frac{e_a}{K_{eq}K_g} + \left[\frac{\pi t}{K_{eq} D_e}\right]^{1/2}}\right] e^{-t/t_b} \qquad \text{(Eq. 49)}$$

where E_i = emission rate of constituent (g/cm^2-sec);

M_o = area loading of constituent (g/cm^2);

l = depth of waste in open landfill (cm);

e_a = volume fraction of air-filled voids in the soil (dimensionless);

K_{eq} = ratio of gas-phase constituent to total constituent in solid waste (dimensionless);

K_g = gas-phase mass transfer coefficient (cm/s);

t = time after waste application to the landfill site (sec);

D_e = effective diffusion coefficient of constituent in the solid waste (cm^2/sec); and

t_b = time constant for biological decay (i.e., time required for 63.2% of constituent to be degraded.

For longer times after application or tilling, when most of the constituent is not present in the soil, the short-term equation will over estimate air emissions. Under these conditions, the following equation is applicable:

$$E = \frac{2 M_0 \quad Keq\ D_e}{l^2} \quad \exp\left[\frac{-D_e\ Keq\ _p{}^2t}{4\ l^2}\right] \quad e^{-t/t_b} \qquad \text{(Eq. 50)}$$

where E = emission rate a long time after application or tilling (g/cm^2-sec); (all other parameters are the same as presented above).

Applicability--

The RTI Land Treatment Model is applicable to sites where liquid or semi-liquid waste is applied to the soil surface. The model assumes that emissions from the surface are limited by diffusion of vapors through the pore space of the soil/waste mixture. The model accounts for removal of organic material from the soil/waste mixture by both biological degradation and air emission.

Limitations--

The model is not applicable to wastes which are easily biodegraded, or to sites with highly porous soils which allow easy vertical migration of the liquid waste. The model does not account for losses to these or other pathways.

SEAMS Model--

The SEAMS landtreatment model is a simplified version of the Thibodeaux-Hwang model. The Thibodeaux-Hwang model was simplified by assuming that the oil layer diffusion length value is low (i.e., that the spilled contaminant has become incorporated into surface soils and is not present as a discrete film on the soil particles). The SEAMS model is designed to calculate an average emission rate over time.

$$E_i = \frac{2DC_sA}{d + \sqrt{\frac{2\,DC_s t}{C_B} + d^2}} \qquad \text{(Eq. 51)}$$

where E_i = average emission rate of component i over time (g/sec);
$D = D_i\,(P_t^{4/3})\,(H_i/RT)$;
D_i = diffusion coefficient of component i in air (cm^2/sec);
P_t = total porosity of the soil (dimensionless);
H_i = Henry's law coefficient for component i ($atm \cdot m^3/gmol \cdot {}^\circ K$);
R = Gas constant ($atm \cdot m^3/gmol \cdot {}^\circ K$);
T = temperature (°K);
C_s = liquid phase concentration of contaminant i in the soil (g/cm^3);
C_B = bulk contaminant concentration in the soil (g/cm^3);
A = contaminated surface area (cm^2);
d = depth of dry zone at sampling time (cm); and
t = time measured from sampling time (sec).

Applicability--

The SEAMS model is applicable to the same situations as the Thibodeaux-Hwang model.

Limitations--

The model is not applicable to wastes which are easily biodegraded, or to sites with highly porous soils which allow easy, vertical migration of the liquid waste. The model does not account for losses to these or other pathways.

4.5.6 Leaks and Spills on Soil

SEAMS Model (Fresh Spills)--

The SEAMS manual presents the following model for estimating volatile releases from spills or leaks where a contaminant pool is visible on the soil surface (41).

$$E_i = K_{iG} C_i^* A \qquad \text{(Eq. 52)}$$

where E_i = emission rate of component i (g/sec);

K_{ig} = gas phase mass transfer coefficient of component i (cm/sec);

C_i^* = vapor concentraiton of chemical i (g/cm^3); and

A = contaminated surface area (cm^2).

Guidance on methods for estimating K_{iG} and C_i^* is presented in the SEAMS manual.

Applicability--

This model can be used for estimating air emissions of volatile species from contaminant pools on soil surfaces.

Limitations--

The model does not consider the soil phase mass transfer resistance, and therefore it is not appropriate for use when spilled contaminants have seeped into surface soils. Also, since the model does not consider the liquid phase resistance, it is only useful for estimating releases of pure compounds.

SEAMS Model (Old Spills)--

The SEAMS manual recommends the use of the SEAMS land treatment model in cases where past spills, leaks or intentional disposal directly onto surface soils have resulted in contaminated surface soils with liquids in the pore spaces. This model is described in Section 4.5.5.

4.5.7 Emission Models for Fugitive Dust

Fugitive dust at hazardous waste sites (airborne wastes or contaminated soils) most commonly results from wind erosion of the wastes or vehicular travel over unpaved contaminated roads. The U.S. EPA has developed equations to estimate fugitive dust emissions arising from vehicle travel on unpaved roads (AP-42). The U.S. Soil Conservation Service (SCS), and Cowherd and Gillette have developed models for predicting fugitive dust emissions resulting from wind erosion from soil surfaces.

SCS Model--

The SCS model (71) takes into account such factors as surface soil moisture content, roughness, and cloddiness, type and amount of vegetative cover, wind velocity and the amount of soil surface exposed to the eroding wind force. The SCS equation can be expressed as:

$$E = f(I^{*},C^{*},K^{*},L^{*},V) \qquad \text{(Eq. 53)}$$

where E = potential annual average wind erosion soil loss;
I^{*} = soil erodibility index;
C^{*} = climatic factor;
K^{*} = soil ridge roughness factor;
L^{*} = field length along the prevailing wind direction; and
V = vegetative cover factor.

For the sake of brevity, the details of the calculation method are not presented in this document. The reader is directed to the Skidmore and Woodruff (59) source document and the SEAMS Manual (41) for further guidance.

Vehicular Traffic--

The US EPA has developed the following equations which can be used to estimate fugitive dust emissions resulting from vehicular travel on contaminated unpaved roads (54);

$$E_{VT} = k(5.9)\ (\frac{s}{12})(\frac{Sp}{30})(\frac{W}{3})\ 0.7\ (\frac{w}{4})\ 0.5\ (\frac{365 - D_p}{365}) \qquad \text{(Eq. 54)}$$

or in metric form:

$$E_{VT} = k(5.9)\ (\frac{s}{12})(\frac{Sp}{48})(\frac{W}{2.7})\ 0.7\ (\frac{w}{4})\ 0.5\ (\frac{365 - D_p}{365}) \qquad \text{(Eq. 55)}$$

where E_{VT} = emission factor for vehicular traffic (lb/vehicle mile traveled, kg/vehicle kilometer traveled);

k = 0.45 = particle size multiplier for particles <10 um (i.e., particles that may remain suspended once they become airborne and which can be inhaled into the respiratory system);

s = silt content of raod surface material (percent);

S_p = mean vehicle speed (mph, kph);

W = mean vehicle weight (tons, Mg);

w = mean number of wheels; and

D = number of days with at least 0.254 mm (0.01 inch) of precipitation per year.

The SCS wind equation computes total fugitive dust emissions due to wind erosion which result from the combination of surface creep, saltation, and suspension. If only the fraction of soil loss that is suspendable and transportable over significant distances by wind is desired, the wind equation must be adjusted (reduced) to reflect emissions from only this phenomenon.

Applicability --
The SCS model is applicable to wind-blown dust.

Limitations --

The SCS model is designed to estimate annual erosion losses and is not reliable when altered to estimate short term emissions (e.g., 24-hour emissions).

Cowherd Model --

Cowherd (55) has developed a predictive equation for estimated respirable particulate emissions from soils of "limited erodibility." The annual average rate of respirable particulate emissions is a function of surface and climatic factors represented by the following equation:

$$E_{10} = 0.83\ f\ (1-V)\ P(U_+)\ (50/PE)^2 \qquad \text{(Eq. 56)}$$

where E_{10} = Annual average PM_{10} emission factor (mg/m^2 - hr).

f = Frequency of disturbance per month.

U_+ = Fastest mile of wind for the period between disturbances (m/sec).

$P(U^+)$ = Erosion potential, i.e., quantity on the surface prior to the onset of wind erosion (g/m^2)

V = Fraction of contaminated surface area covered by continuous vegetative cover.

PE = Thornthwaite's Precipitation Evaporation Index.

Soils of limited erodibility are nonhomogeneous surfaces impregnated with nonerodible elements (stones, clumps of vegetation, etc) and contain a finite reservoir of erodible material. In contrast, bare surfaces of finely divided material are characterized by an "unlimited reservoir" of erodible particles. Guidelines for characterizing the wind erosion potential of a surface and for evaluating the terms in the Cowherd model are presented in the EPA manual entitled Rapid Assessment of Exposure to Particulate Emissions from Surface Contamination Sites (55).

Applicability --

The Cowherd model is applicable for estimating the emission rate of respirable (less than 10 microns in diameter) wind-blown dust from surfaces of limited erodibility.

Limitations --

The model is designed for estimated an annual average emission rate. It is not designed to estimate short-term emissions.

Gillette Model --

Gillette (55) has developed the following model for estimating annual respirable particulate emissions from wind erosion of surfaces with an "unlimited reservoir" of erodible particles:

$$E_{10} = 0.036\ (1-V) \left[\frac{U}{U_t}\right]^3 F(x) \qquad \text{(Eq. 57)}$$

where E_{10} = Annual average PM_{10} emission rate (g/m^2 -hr).
V = Fraction of contaminated surface vegetative cover.
U = Mean annual wind speed (m/sec).
U_t = Threshold value of wind speed at 7m (m/sec).
x = $0.886\ U_t/U$ (dimension less ratio).
$F(x)$ = Empirical function.

Soil moisture is not taken into account in this equation because highly erodible soils do not readily retain moisture. Gillette modified equation 55 slightly to obtain the following expression for estimating worst-case 24-hour average emission rates:

$$E_{10} = 0.036\ (1-V)\ (U_+ -2)^3 \qquad \text{(Eq. 58)}$$

where E_{10} = 24-hour average PM_{10} emission rate (g/m^2 -hr).

V = Fraction of contaminated surface area covered by vegetation.

U_* = Mean annual fastest mile of wind (m/sec).

It should be noted, however, that the 24-hour average emission rate predicted by this equation is based on annual average parameter values for U_*. Guidelines for evaluating the terms in the Gillette equations are presented in the EPA manual entitled Rapid Assessment of Exposure to Particulate Emissions from Surface Contamination Sites (55). The reader is referred to this document for a more detailed discussion of the models.

Applicability --

The Gillette models are applicable for wind-blown dust emissions from highly erodible surfaces. Both annual and short-term emissions can be estimated.

Limitations --

The short-term model is based on annual average parameter values and may overestimate the 24-hour average emission rate.

Vehicular Traffic--

The U.S. EPA has developed the following equations which can be used to estimate fugitive dust emissions resulting from vehicular travel on contaminated unpaved roads (54):

$$E_{VT} = k(5.9)\ (\frac{s}{12})\ (\frac{Sp}{30})\ (\frac{W}{3})^{0.7}\ (\frac{w}{4})^{0.5} \left[\frac{365-D_p}{365}\right] \qquad \text{(Eq. 59)}$$

or in metric form:

$$E_{VT} = k(1.7)\left(\frac{s}{12}\right)\left(\frac{Sp}{48}\right)\left(\frac{W}{2.7}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left[\frac{365-D_p}{365}\right] \qquad \text{(Eq. 60)}$$

where E_{VT}= emission factor for vehicular traffic (lb/vehicle mile traveled, kg/vehicle kilometer traveled);

k = C.45 = particle size multiplier for particles <10um (i.e., particles that may remain suspended once they become airborne and which can be inhaled into the respiratory system);

s = silt content of road surface material (percent);

S_p = mean vehicle speed (mph,kph);

W = mean vehicle weight (tons,Mg);

w = mean number of wheels; and

D_p = number of days with at least 0.254mm (0.01 inch) of precipitation per year.

To estimate fugitive emissions due to vehicle travel for a given time period, the emission factor, EVT defined above, is multiplied by the vehicle miles traveled during that time period. Maximum release conditions may be estimated by using a small value of D_p in the model to reflect assumed drought conditions. Average emissions can be estimated by using annual average value for D_p. Whenever possible, values for climatic and soil parameters should be obtained for the particular site in question. Cowherd et.al. (55) provides default values for model parameters that can be used when site-specific data are not available.

Applicability--

The AP-42 dust model is only applicable to dust resulting from vehicular traffic.

4.5.8 Additional Models

Additional models identified but not included here are: Hwang's modification of Farmer, (52,60) RTI Open Dump Model, (44) Hartley Method, (37,61) Hamaker Method, (61) and Dow Method (61). The latter three equations were developed for volatilization of pesticides applied to soil.

4.5.9 Non-Aerated Lagoons

Mackay and Leinonen Dynamic Two-Film Model--

This dynamic model (56,57) best serves those instances involving isolated disposal of a given quantity of waste, as opposed to the steady-state scenario offered by the other models. Laboratory validation of this model was reported (57).

This model assumes that nearly stagnant films of well mixed bulk air and water systems occur on both sides of the liquid/air interface.

$$N_i = K_{iL} \ (C_i - P_i/H_i) \qquad \text{(Eq. 61)}$$

$$C_i = P_i/H_i + (C_{io} - P_i/H_i) \exp(-K_{iL} \ t/L)$$

where N_i = mass flux rate (mol/m2-hr);

K_{iL} = overall mass transfer coefficient (m/hr);

C_i = concentration of i at time t (mol/m^3);

P_i = equilibrium partial pressure of i in the vapor (atm);

H_i = Henry's Law constant for i (atm-m^3/mol);

C_{io} = initial concentration of i at t = 0 (mol/m^3);

t = time (hr); and

L = depth of lagoon (m).

Applicability--

The model offers an alternative to the steady-state scenario. However, Wetherold (37) reports that despite its theoretical validity, the model is difficult to apply to the "real world." The input parameters are difficult to determine or find in available literature. And, this model best applies to the emissions of single compounds.

Limitations--

The model fails to provide for white caps, thermoclines, eddy diffusion and other similar phenomena, tending to under-predict emissions when these conditions occur at the lagoon.

Thibodeaux, Parker and Heck Model--

This model (53), which can be applied to both non-aerated and aerated lagoons, evolved from basic accepted theories of mass transport. It is used to determine emission rates of individual compounds, assuming that the concentration of each compound remains constant in the aqueous phase (it does not interact with the other compounds present). It also assumes that the influx of the compound is steady, that its biodegradation rate is steady, and that the lagoon surface can be clearly separated into either quiescent (non-aerated) or turbulent (aerated) zones.

To use the equation, four mass transfer coefficients must be determined from impartial relationships.

$$q_i = M_i K_{1i} (X_i - X_i^*) \qquad \text{(Eq. 62)}$$

For each volatile component i:

$$K_1 = (K_1^t A_t + K_1^n A_n)/(A_t + A_n) \qquad \text{(Eq. 63)}$$

$$\frac{1}{K^t} = \frac{1}{k^t} + \frac{1}{Hk_g^t} \qquad \text{(Eq. 64)}$$

$$\frac{1}{K_l^n} = \frac{1}{k_l^n} + \frac{1}{Hk_g^n} \qquad \text{(Eq. 65)}$$

where q_i = flux of component i from the lagoon surface (g/cm2-sec);

M_i = molecular weight of component i (g/g-mol);

K_{li}= overall liquid-phase mass transfer coefficient for component i (mol/cm^2-s);

X_i = mole fraction of component i in the aqueous phase (this must be measured); and

X_i*= mole fraction of component i in equilibrium with the mole fraction of i in air, Y_i (if Y_i is assumed to be negligible, X_i* can equal 0);

K_l^t, k_l^n = overall liquid-phase mass transfer coefficient for aerated non-aerated zones of a lagoon, respectively (mol/cm^2-s); and

A_t, A_n = surface areas of aerated and unaerated zones, respectively (cm);

K_l^t, k_l^n = individual liquid phase mass transfer coefficients for the aerated and unaerated zones, respectively (mol/cm-s);

K_g^t, K_g^n = individual gas phase mass transfer coefficients for the aerated and unaerated zones, respectively (mol/cm-s); and

H = Henry's Law constant in mole fraction form (y = Hx).

Applicability--

The Thibodeaux, Parker, and Heck model is applicable to aerated, non-aerated, and combined lagoons. The model assumes steady-state conditions and, therefore, is applicable to undisturbed lagoons. The model is probably not applicable to disturbed (disturbed sludge) conditions.

Limitations--

The accuracy of this model has not been verified as of 1982. Wetherold (37) expressed some skepticism regarding the accuracy or availability of some parameters necessary for the calculation of the mass transfer coefficients. Also, the model requires additional development to satisfy the need for a predictive model capable of predicting total VOC emissions from a lagoon containing a complex mixture of compounds (37).

One way to deal with this, as suggested by DeWolf (53), is to sum up the emissions estimated for several classes of compounds by selecting a representative compound from each class. Acknowledging this selection as "arbitrary", DeWolf provides some suggestions, noting that some compounds are more likely to be encountered and those in mid-molecular weight range of 4 to 8 carbons are "likely to dominate in frequency of occurrence". He suggests:

Class	Compound
Paraffins	Hexane
Olefins	Butene
Aromatics	Toluene
Halogenated hydrocarbons	Methylene chloride
Oxygenated hydrocarbons	Acetone

Smith, Bomberger, and Haynes Model--

The Smith et al. model (37) is applicable to emissions prediction for highly volatile compounds in a lagoon setting. The model is not applicable to low and intermediate volatility compounds. Also, liquid phase resistance should be the controlling resistance.

The volatilization rate is expressed as a first-order kinetic equation.

$$E = (K^a)_{env}\ (c) \qquad \text{(Eq. 66)}$$

$$(K^a)_{env} = \frac{K^a}{K^\circ_{Lab}}\ (K^\circ)_{env} \qquad \text{(Eq. 67)}$$

where E = mass emission rate per unit volume (lbs/gal-day);

$(K^a)_{env}$ = volatilization rate constant for compound a in the environment (day^{-1});

c = concentration of compound a (lbs/gal);

$\frac{K^a}{K^\circ_{Lab}}$ = ratio of volatilization constants of compounds a and oxygen as K lab measured in laboratory (dimensionless); and

(K°)env = oxygen reaeration rate in the environment (day^{-1}).

Applicability--

The model is applicable to volatilization of high volatility compounds from non-aerated waste disposal lagoons.

Limitations--

The model is limited in that it is designed to predict emission rates of highly volatile individual compounds and it may be difficult to apply to complex multicomponent wastes. The model is not appropriate for estimating emissions of low or intermediate volatility compounds. Also, Wetherold (1982) notes that determining the ratio of volatilization constants of a compound (K^a/K°) is expensive in the laboratory; attempts to estimate this ratio simply using diffusion coefficient values increase the model's overall uncertainty.

Shen Model--

The Shen Model (48,58) presents an empirical equation for determining volatile emissions from lagoons. The Shen Model is (48):

$$ER_{P_i} = 18 \times 10^{-6}\ K_{L_i}\ A\ C_i \qquad \text{(Eq. 68)}$$

where ER_{P_i} = emission rate potential of compound i (g/sec);
A = lagoon surface area (cm^2);
C_i = concentration of compound i in lagoon (mg/l); and
K_{Li} = liquid-phase mass transfer coefficient of compound i (g-mol/ cm^2-sec).

and,

$$K_{Li} = 4.45 \times 10^{-3} (M_i)^{-0.5} (1.024)^{t-20} (U)^{0.67} (H)^{-0.85} \qquad \text{(Eq. 69)}$$

where M_i = molecular weight of compound i (g/mole);
t = lagoon surface temperature (o_C);
U = surface velocity = 0.035 wind speed (cm/sec); and
H = average liquid depth of the lagoon (meter).

Applicability--

The Shen Model is applicable as a screening technology to estimate volatile emission rates from lagoons. It appears, from Shen's discussion, that the model assumes the lagoon is a dilute water solution, although this is not explicitly stated. Shen indicates that the model should only be used when "emission rates and risks are clearly acceptable or unacceptable."(48)

Limitations--

The model should be limited to use as a screening technology.

RTI Model--

The RTI Model is a simple volatile constituent mass transfer model (44):

$$E_i = K_i A\, C_i \qquad \text{(Eq. 70)}$$

where E_i = air emissions for component i from the liquid surface (g/sec);
K_i = overall mass transfer coefficient for component i (m/sec);
A = liquid surface area (m^2); and
C_i = concentration of component i in the liquid phase (g/m^3).

The calculation of the mass transfer coefficient (K_l) will depend on whether the lagoon is quiescent, turbulent, a combination of quiescent and turbulent, or has an oil film. In addition, the equation can be adjusted to account for losses due to biodegradation. Several methods for calculation of K_L are given in the listed reference as well as examples for applying the model to specific site types.

Applicability--

The RTI Model is applicable to assessing volatile emissions from aerated and non-aerated lagoons. The model is applicable to quiescent and turbulent lagoons and can be adjusted to include biodegradation, although the toxic nature of most waste lagoons will limit biological activity. The model is applicable to both undisturbed and disturbed site conditions.

Limitations--

The model is not applicable to lagoons with a surface crust. While the calculation of the mass transfer coefficient includes wind speed for quiescent lagoons, the turbulent lagoon calculations appear to consider wind speed to have negligible affect on the emission rate.

4.5.10 Aerated Lagoons

Thibodeaux, Parker, and Heck Model--

This model is described in 4.5.9.

RTI Model--

This model is described in 4.5.9, and can be adjusted for aeration.

Chemdat 6--

EPA has published a number of models for RCRA sites, including models for aerated lagoons (75). This same model is also available in a more user-friendly version known as the Surface Impoundment Modeling System (SIMS).

4.5.11 Sources of Model Input Data

The models presented in the previous sections require a wide variety of input parameters. Table 17 provides a list of references which contain tabulated data for some of the common chemical and soil property parameters; hwoever, many of the models require additional input data such as mass transfer coefficient, soil vapor concentration, etc. In these cases, the reader is referred to the source document for each model. The authors generally provide guidance on methods for estimating speicific model parameters.

In addition, a number of existing data bases may be useful for supplying the data requirements of the emission model. Data bases that contain landfill facility data, chemical property data, geophysical data, and meteorological data are described below. More detailed information regarding the data bases is contained in Appendix D. Physical and chemical properties for compounds frequently encountered at Superfund sites are given in Appendices F and G.

Landfill Data Bases

Five data bases have been identified that may provide the landfill facility data required to estimate emissions using available techniques. These are:

- Solid waste landfill survey;
- National Survey of Hazardous Waste Treatment, Storage, Disposal, and Recycling Facilities;
- National Survey of Hazardous Waste Generators;
- Industrial Subtitle D Facility Study - Mail Questionnaire; and
- Industrial Subtitle D Facility Study - Telephone Survey.

Chemical Property Data Bases

- EPA Chemical Properties Data Base; and
- National Library of Medicine Online Service (HSDB).
- EPA GEMS Database

Geophysical Data Bases

- GEMS Geoecology Data Base; and
- NCDC Soil Temperature Data Base.

Meteorological Data Bases

- STAR Data Base; and
- NCDC Data Bases.

TABLE 17. DATA SOURCES FOR SELECTED MODEL PARAMETERS

Model Parameters	Reference Number
Henry's Law Constant (H)	44, 51, 56, 62
Diffusion Coefficient (D)	41, 44, 53, 63
Soil Porosity (P_t,P_a)	41, 64
Vapor Pressure (P*)	44, 51, 53, 56, 63
Methane Generation Rate Constant (k)	73, 74
Potential Methane Generation of Refuse (L_0)	73, 74

SECTION 5
CASE STUDIES

Section 5 is a collection of five case studies that demonstrate the protocol described in this manual for developing BEEs. The purpose of this section is to document different experiences regarding site investigation and characterization and to demonstrate the protocol for developing BEEs as applied to these case studies. The sites selected represent different regions of the country, different types and distributions of waste, varying levels of air emissions potential, and varying levels of historical air pathway analyses (APA) performed in support of the Remedial Investigation/Feasibility Study (RI/FS) process.

Only the first case study demonstrates application of the complete protocol. The protocol was implemented only partially at the other sites. The assessment techniques used (or not used) in these case studies do not necessarily represent the best or most technically suitable assessment techniques. Many factors influenced the decision-making process concerning the development of BEEs leading to air pathway evaluations. Also, the work at these sites was conducted without the benefit of a formalized protocol for designing APA programs and developing BEEs.

5.1 CASE STUDY 1: PETROLEUM WASTE LANDFILL/LAGOON

Case Study 1 is a disposal area for wastes from a defunct refinery.

5.1.1 Site History

The petroleum waste site resulted from years of dumping bottom sludge from refinery vessels and tanks at a disposal area located adjacent to the refinery. The on-site disposal activity was performed as general refinery upkeep and was typical of the oil industry at that time.

This small refinery was located in Southern California between the foothills of a mountain range and a small community. The refinery dumped its wastes on site from about 1930 to 1950. In 1952, the refinery was dismantled except for an old garage and several tanks. Since 1953, the site has been a crude oil pumping station. No known dumping has resulted from the pumping station operation; therefore, all waste dates back over 35 years. At present, the property is separated from an elementary school and a number of residences by a fence and a drainage channel. The site is shown in Figure 22.

The refinery dumped most of its sludge in a landfill on the western edge of the property. The landfill covered approximately one acre of surface area and was bermed at the middle at some unknown time, thereby separating the landfill at the north end from a lagoon at the south end. The landfill is believed to have resulted from dumping soil into the landfill to solidify the liquid waste. Investigations of the site disclosed that the entire landfill/lagoon contained roughly 11,100 cubic yards of waste to a depth of about 6 feet. The waste was an oily sludge, with an odor and appearance typical of refinery wastes.

The site is subject to hot summers and mild winters. Precipitation is approximately 20 inches per year, occurring predominantly during the winter months. During site work, winds generally were light and easterly or northeasterly during cooler periods. During warmer periods, onshore sea breezes yielded moderate breezes from the west and southwest. The residential neighborhood was downwind of the lagoon and landfill most of the time.

5.1.2 Objectives

The objectives of the site work, from an air pathway perspective, were several-fold: provide estimates of the undisturbed and disturbed site emissions; to use BEEs to develop a mitigation plan; and to conduct ambient monitoring during the remedial investigation and mitigation to ensure worker and community protection through the setting of appropriate action levels. Table 18 summarizes the activities conducted at the site to address the air pathway. These activities are described below.

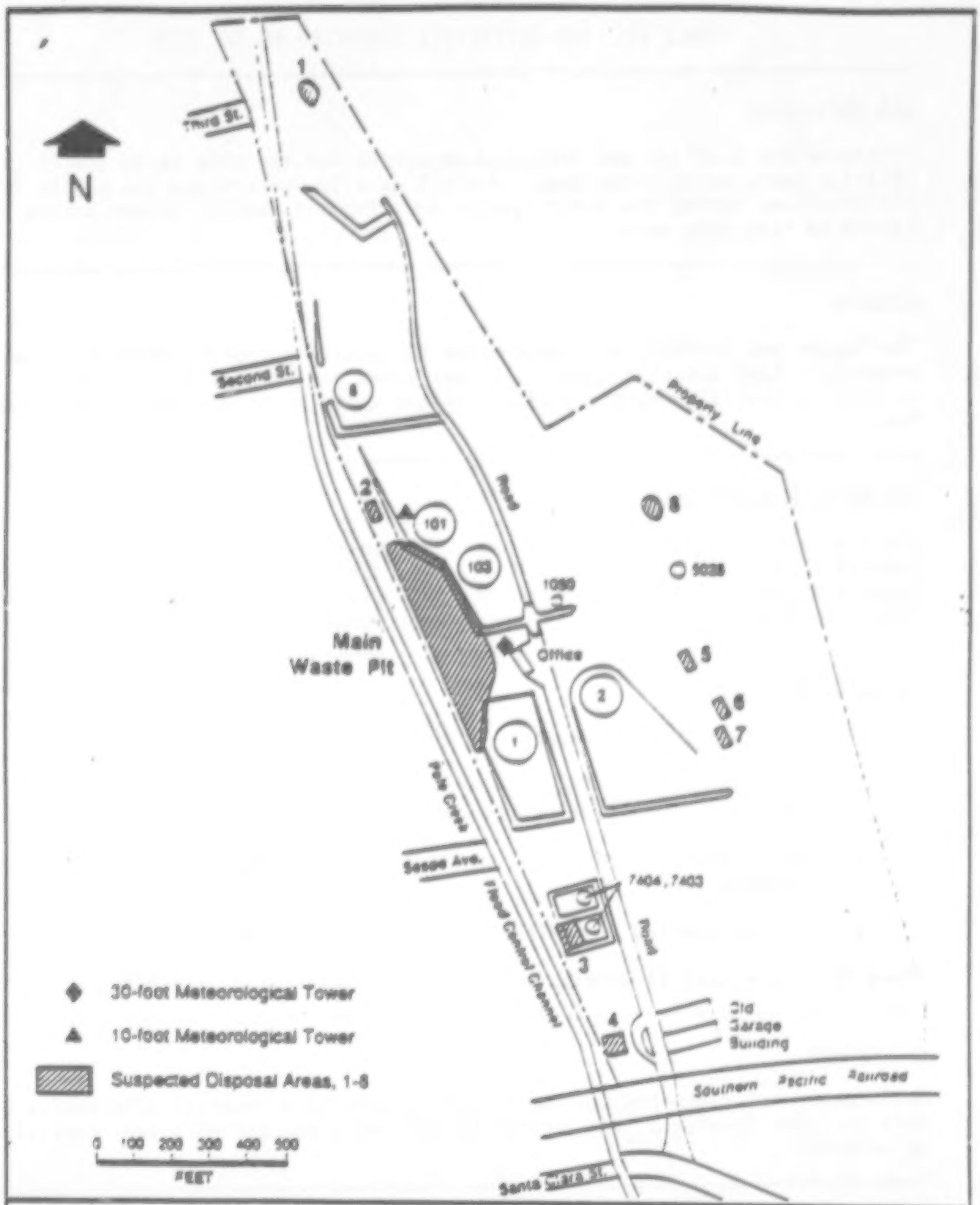

N
1
Third St.
Second St.
8
Property Line
Road
2
101
103
8
5028
1050
Main Waste Pit
Office
5
2
6
7
1
Pole Creek
Sespe Ave.
Flood Control Channel
7404, 7403
Road
3
4
Old Garage Building
Southern Pacific Railroad
Santa Clara St.
30-foot Meteorological Tower
10-foot Meteorological Tower
Suspected Disposal Areas, 1-8
0 100 200 300 400 500
FEET

Figure 22. Location of suspected disposal areas.

TABLE 18. APA ACTIVITIES CONDUCTED AT THE SITE

APA Objectives

Determine the baseline and disturbed emissions for the site using direct emission measurement techniques. Protect on-site workers and the public from air emissions during the investigation by using air monitoring and action levels to stop site work.

Scoping

The lagoon and landfill were determined to contain petroleum waste that had a moderately high volatile organic air emissions potential. Particulate emission potential from the sludge/tar-like solid waste was considered to be low.

Screening Measurements

The site was surveyed using real-time instruments (indirect technique) for indicator compounds on a grid system. Soil samples were collected for head space analyses to assess air emissions potential (direct technique). These data were used to design the in-depth measurement strategy.

In-Depth Measurements

The in-depth emission measurements included:

- Undisturbed baseline emission measurements using the surface emission isolation flux chamber;
- Disturbed baseline emission measurements using the downhole emission chamber; and
- Air monitoring for worker and public protection.

These data were used to develop undisturbed and disturbed site BEEs.

Mitigation

Undisturbed and disturbed BEEs were used to develop a remedial alternative that included excavation and removal of the waste and air emissions control techniques.

5.1.3 Scoping

In late 1980, the owner sought regulatory agency approval to remove the waste and apply it to site roads. California's Regional Water Quality Control Board denied the request after two sets of samples, sent to two independent laboratories, disclosed high lead concentrations in the waste. The owner then sought a more thorough environmental evaluation of the site and recommendations for remediation.

The initial task in completing the scoping phase of the site characterization was a review of existing data. Information was collected from the owner's site files, from files at a similarly operated refinery, from public agencies, and from available references. The collected data were reviewed to provide a working knowledge of the site history, conditions, and environmental setting. Essentially no activities had been conducted to determine waste volume, environmental impacts, emissions characteristics, or waste existence and type in other suspected disposal areas.

The site investigation was initiated by a site inspection. The inspection served to familiarize the crew with the site, to locate special features, and to assist in the development of appropriate sampling methods. This undertaking identified two types of wastes: a tar-like waste and a granular waste that gave off fumes and white vapors when it came in contact with water. The granular waste caused eye irritation and hindered breathing. Based on this site scoping, the potential for volatile air emissions during site mitigation was deemed to be high and further site characterization activities were initiated.

5.1.4 Overview of Fieldwork for Site Characterization

An undisturbed emission survey (see 5.1.5) was completed to assess the atmospheric impacts of volatilized compounds under prevailing site conditions. The emission survey used indirect real-time instrument measurement techniques. Knowledge of the type of waste indicated that total hydrocarbons and benzene, as representative of aromatic species, were good indicator compounds for volatile emissions from the petroleum waste. It was also possible that sulfur dioxide (SO_2) could be an air contaminant from the waste. Thus, total hydrocarbons, benzene, and SO_2 were selected as the indicator compounds. Other compounds may have been equally well suited for use as indicators, but the compounds selected proved to be adequate. Testing for these compounds showed low emissions (less than three times background levels) of total hydrocarbons, benzene, and SO_2. This result was obtained by comparing on-site emission rate data to background or off-site data. It was concluded that no significant atmospheric impacts existed on or off site for undisturbed site conditions.

To assess the potential impacts of air emissions of the combined site during remediation and to provide adequate monitoring for on-site personnel and nearby residences, a monitoring program was conducted that included: constant meteorological monitoring at two stations; monitoring for emissions from waste disturbance activities at the property boundary between the waste and the nearby residences; and surveying of corehole borings.

Two meteorological towers (see Figure 22) were used to collect continuous data. A 33-foot tower equipped with meteorological instrumentation collected the primary meteorological site data during the field activity. In addition, a 10-foot tower provided micro-meteorological wind speed and wind direction data. The towers were positioned upwind and downwind of the landfill and lagoon. Meteorological data were used in receptor modeling, in conjunction with the measured emission rate data, for planning remedial options.

Additional waste characterization efforts were performed. Five core holes were drilled through the waste and into the soils below the waste to permit sampling of the waste and soils and examination of waste and soil stratification and physical properties. They also provided a means for measuring volatile species emissions as a function of depth in the waste. Wastes were found to be only 5 or 6 feet deep over the 50,000 square-foot pit area, for a total of approximately 11,100 cubic yards of wastes in the landfill and lagoon. Wastes were generally soft and semi-fluid in the lagoon and hard or soil/waste mixtures in the landfill. The waste had a pH below 2.0, contained varying levels of trace metals (including high concentrations of lead in some samples), and had a very high percentage of organic material. Soils below the wastes were predominantly alluvial gravels mixed with sand and silt. The soils rapidly buffered acidic waste leachate. Trace metals were found in varying concentrations and no apparent trend existed with depth. The underlying soils had been impacted by low levels of hydrocarbons originating in the waste pit.

In addition to the air-related work described above, extensive work was undertaken to assess the impact of the site on local ground water. Also, eight small areas suspected of being former waste disposal areas were investigated.

The site inspection data were reviewed and a subsequent site investigation plan was developed. This included an undisturbed emission survey, air monitoring on-site and at the fenceline during drilling and sampling of wastes in the landfill and lagoon, and an emissions survey under disturbed conditions to estimate the potential for emissions during possible future disturbance of the wastes during an excavation activity.

5.1.5 Undisturbed Emissions Survey

Both screening and in-depth measurements were performed.

Screening Measurements--

A survey of the undisturbed surface emissions was conducted. First, the main waste pit disposal area was surveyed and a map was prepared with a grid system overlying the waste area to provide location reference. An emissions survey was performed which consisted of a real-time instrument survey (an indirect measurement screening technique) for indicator species at randomly selected grid points mapped over the landfill and lagoon. This survey provided general data on the level of gas concentrations from the landfill and lagoon, identified potential areas of higher concentrations, documented background conditions (i.e., gas species concentration background levels), and provided input into the safety program, ensuring adequate worker/operator protection. This screening technique was selected because it was a quick and inexpensive way to survey the site for areas of high air emissions potential. These data could then be used to design the in-depth measurement approach.

During the emission screening, portable, real-time monitors were used to determine sulfur dioxide (SO2), total hydrocarbon compounds (THC), and aromatic compounds (benzene). THC measurements were made with an organic vapor analyzer (OVA). SO_2 measurements were made with an electrochemical cell instrument. The HNU analyzer was used to detect aromatic species reported as benzene. SO_2, THC, and benzene, as well as surface and air temperature, were measured at 27 grid node points under quiescent conditions. The portable analyzers provided rapid feedback, but could not differentiate between various hydrocarbon or sulfur species.

For this site, benzene, SO_2, and THC were used as indicators of air emissions. Benzene is a carcinogenic contaminant representative of aromatic compounds. Sulfur dioxide was a possible inorganic air contaminant on site. Total hydrocarbons were monitored for an indication of total organic air emissions.

In-Depth Measurements--

After completion of the screening measurements, in-depth measurements were conducted to quantitate the gas emissions from the undisturbed site for risk assessment purposes and to aid in siting drilling locations. The need for this type of sampling was determined before any screening measurements were performed, based on the waste type and the proximity of receptors (i.e., the suspected large volume of highly volatile wastes was considered likely to cause significant air impacts during any remedial waste removal or disturbance activities). Direct emission measurements were performed using an emission isolation flux chamber. This in-depth technique was selected because it is ideally suited to obtain emission rates from homogenous area sources. The flux chamber is relatively easy to use and multiple measurements (i.e., 8 to 10) can be obtained in one day. Gas samples collected from the flux chamber outlet line were analyzed using real-time analyzers. Samples also were collected in gas canisters for detailed hydrocarbon speciation in an off-site laboratory.

The site was divided into zones of high and low emissions potential based on plotted results from the real-time instrument survey. Locations for in-depth measurements were randomly selected from grid cells in these different zones. Based on the results of the real-time instrument survey, nine flux chamber measurements were performed to assess the undisturbed emission from the main landfill/lagoon. The flux chamber was constructed and operated as described in Section 4. Measurements at a given grid point were typically made over a 40-minute time period.

Chemical measurements performed on the air leaving the emission chamber included:

- Continuous determination of SO_2 (Interscan);
- Continuous determination of THC (OVA);
- Continuous determination of benzene (HNU); and
- Grab sampling for organic speciation (Photovac 1010).

Undisturbed Emission Survey Results--

A total of 27 grid nodes were sampled, including sampling at five background locations (upwind of each block), five duplicate sample points, and sampling at one control point location at three different times of the day (morning, noon, and afternoon). The control point was one of the grid points that was regularly sampled to establish an estimate of the temporal variability in emissions at the site.

Very low gas concentrations were observed over the exposed waste. Most of the screening measurements showed background levels at the locations sampled for SO_2, THC, and benzene as shown in Table 19. Moderately low levels of undisturbed emissions were observed over exposed waste in the lagoon and the landfill. Table 20 provides undisturbed site emissions data.

TABLE 19. SUMMARY OF SCREENING MEASUREMENTS OF UNDISTURBED WASTE

	Range of Values					
Number of Measurements	SO_2 (ppm)		THC (ppm)		Benzene (ppm)	
	Peak	Average	Peak	Average	Peak	Average
41	0.005	0.005	2-4[a]	2-4[a]	0.01-0.80[b]	0.01-0.70[b]

[a] Differences probably due to instrument drift.

[b] Background levels only detected at 30 of 41 points.

TABLE 20. CASE STUDY 1: SUMMARY OF UNDISTURBED SITE EMISSIONS DATA

Lagoon Location (Surface)	SO_2 (mg/m^2, min^{-1})	THC[a] (ug/m^2, min^{-1})	Benzene[b] (ug/m^2, min^{-1})
#1	0.14	1.8	4.7
#2	0.14	120	470
#3	0.14	7.3	43
#4	0.14	44	1.8
#5	5.6	7.3	11
Average	1.2	36	98
Landfill Location			
#1	0.14	7.3	3.6
#2	1.4	29	3.6
Average	0.77	18	3.6

[a] As determined by portable FID (OVA).

[b] As determined by portable PID (HNu).

The results of the screening and in-depth emissions testing showed that:

- The emissions were highest in the landfill and lagoon where wastes were exposed (especially where natural disturbances occurred; i.e., cracking of surface, waste seeps, etc.);

- Control point sampling at various times of the day (same location) indicated a large temporal variation in emissions due primarily to solar surface heating;

- Areas surrounding the combined site or in overburden on top of the waste material showed background levels of emission; and

- Volatile emission rates from the combined site (landfill and lagoon) were low for SO_2 and benzene under undisturbed conditions. For steady-state conditions: SO_2 emission rates ranged from background to 5.6 ug/m^2 $minute^{-1}$; THC emission rates ranged from background to 120 ug/m^2, $minute^{-1}$; and benzene from background to 470 ug/m^2, $minute^{-1}$. Emissions did show a high dependence on diurnal temperature fluctuations with more emissions observed during the hottest periods, as expected. The field photovac analytical capability provided limited hydrocarbon speciation data that helped direct more detailed hydrocarbon sampling and analysis. The photovac data were not used to determine emission estimates.

5.1.6 Disturbed Emissions Survey

Both screening and in-depth measurements were performed.

Screening Measurements--

Samples of soil/waste were collected during drilling at each sampling point as part of the screening survey. Screening for volatile organic compounds (VOCs) in these samples was performed at the field site with a Photovac 1010 portable photoionization gas chromatograph (GC). This GC has part-per-billion (ppb) level sensitivity for milliliter volumes of air. Soil and waste samples were collected (2 to 3 grams) and stored in 40 mL VOA vials with Teflon\ SEPA. The vials were equilibrated in a 30°C water bath for 30 minutes prior to the head space analysis for VOCs. This sampling procedure is considered a direct measurement screening-technique.

During disturbance activities, fenceline monitoring for SO_2 and benzene was conducted using portable real-time instruments. Also meteorological conditions were monitored during all work disturbing the site. Action levels were established to require cessation of site activities if exceedances were noted (none occurred) to protect the local community.

Downwind and border monitoring consisted of three activities:

- SO_2 and THC were monitored immediately downwind of the disturbance activity;
- SO_2 and THC were monitored at a mobile unit approximately 40 feet downwind of the initial disturbance activities; and
- SO_2 and benzene were monitored at a mobile unit at the downwind fenceline between the drilling operation and the nearby residences.

Standard monitoring procedures (see Volume IV of this series of manuals) were used in operating the border and downwind stations. Air analyzers were operated according to written quality control protocols and continuous data printouts were collected using strip chart recorders. The monitoring stations were positioned each day based on wind direction data from the meteorological stations.

In-Depth Measurements--

Downhole emission measurements at various depths in the waste were conducted during drilling activities to determine an emissions "profile" in the waste. These data were used to characterize the waste properties and to predict potential gas emission from the wastes if they were excavated.

Downhole emissions measurements were performed using the direct emissions measurement technique (i.e. downhole flux chamber). This technique is considered an in-depth measurement technique and was applicable for the landfill and the lagoon. The plexiglas chamber had an exposed surface area of 0.00318 m^2. The chamber input and output lines were 40 feet long, facilitating flux measurement to 30 feet below land surface.

Five locations for drilling were selected as part of the solid waste investigation. They are shown in Figure 23. They were representative of waste bodies and were equally spaced across the waste areas. Hydrocarbon samples were collected in 2.8-liter stainless steel canisters. After collection, the canisters were shipped to an off-site laboratory for analysis.

A total of 18 downhole emission measurements were performed and realtime data for SO_2, THC, and benzene were collected at each point using the real-time analyzers. Canister samples were collected at six locations (at various depths within the five core holes) for speciation analyses. Canister samples were not collected at all sampling locations in an effort to conserve project resources. The indicator compounds were used to represent air emissions potential in the absence of the canister samples.

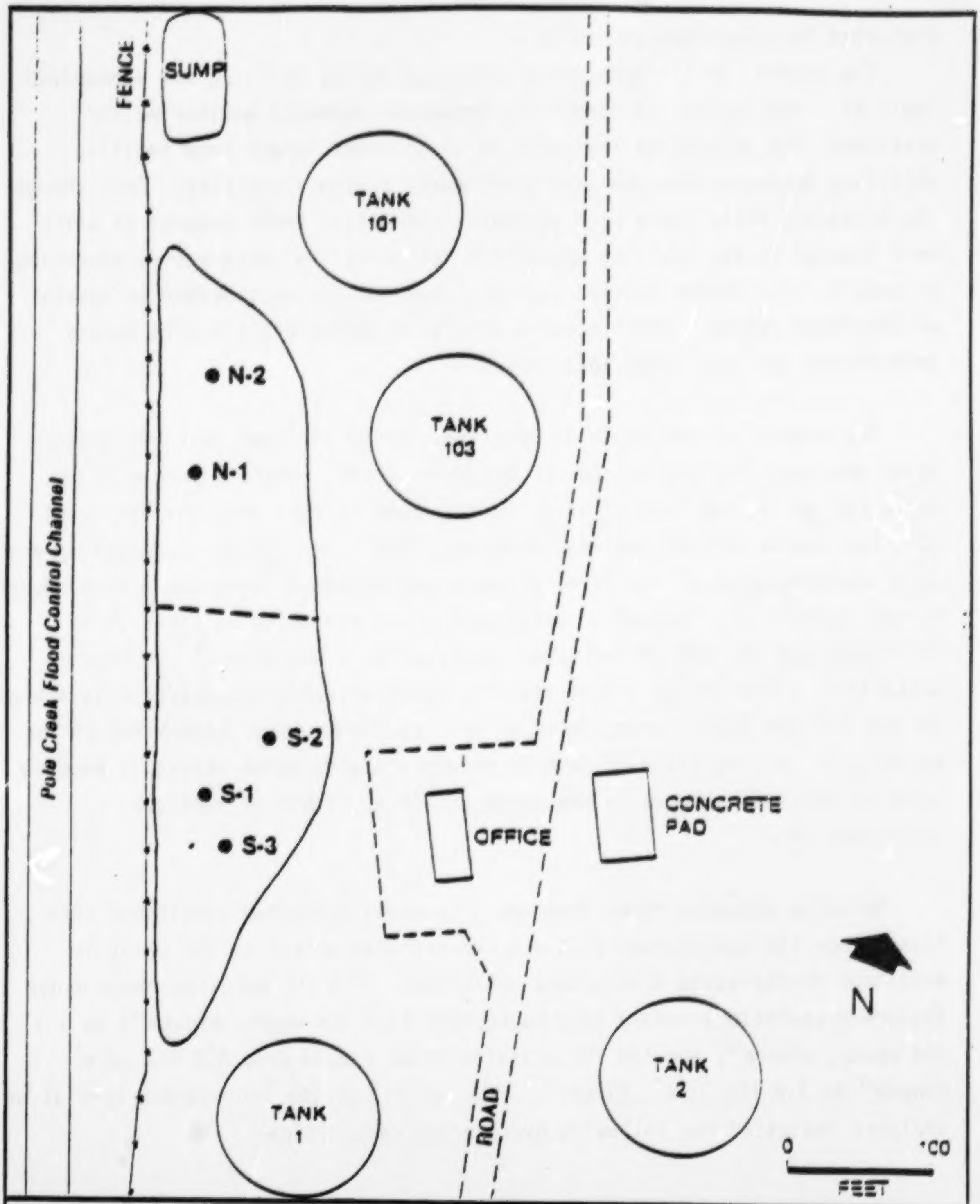

FENCE
SUMP
TANK 101
N-2
TANK 103
N-1
Pole Creek Flood Control Channel
S-2
S-1
S-3
OFFICE
CONCRETE PAD
N
TANK 1
ROAD
TANK 2
0
100
FEET

Figure 23. Location of waste soil coreholes.

Disturbed Emission Survey Results--

The results of air monitoring conducted during drilling are summarized in Table 21. The results of border and immediate downwind monitoring for disturbed site activities indicated no significant impact from fugitive emissions downwind from the site (northeast) boring activities. Even though the disturbed waste had a high emissions potential, small amounts of waste were exposed in the drilling operations following the conservative operating procedure. The border station was positioned on the west border to assess neighborhood safety. This location also provided valuable onsite safety information for site operations personnel.

The results of the downhole emissions survey included peak and steady-state emissions for SO_2 and THC at the given depth. Benzene data were not collected due to the lack of an extractive pump in that analyzer that could pull the sample through the long sampling lines. The steady-state values are more representative of the level of emissions expected involving a disturbance of the waste (i.e., removal). Data results are presented in Table 22 to illustrate the SO_2 and THC emissions observed as a function of the type of waste/soil. This format illustrates the relative emissions characteristics of SO_2 and THC per depth in the cores as well as the emission tendencies of the waste/soil. A comparison of peak to steady-state emission values is used to identify emission sources in the waste pit (i.e., limit of vertical contamination).

Volatile emission rates from the site under disturbed conditions were higher than the undisturbed site and demonstrated potential for volatile emissions during waste disturbance activities. The SO_2 emission rates under disturbed conditions ranged from background (1.6 EE4 ug/m^2, minute^{-1}) to 1.1. EE6 ug/m$_2$, minute^{-1}, and the THC emission rates ranged from 3.8 EE3 ug/m^2, minute^{-1} to 3.8 EE6 ug/m^2, minute^{-1}. The results of the hydrocarbon speciation analyses indicated the following hydrocarbon composition:

TABLE 21. DOWNWIND/BORDER MONITORING RESULTS

Location	Date	Species	High Level[d] (ppmv)	Duration
West Border (Fence) Core S-1	08/02/83 08/02/83 08/02/83	Benzene[a]	0.12^c Background Background	Elevated Background
Downwind 40 m Core S-2	08/03/83	SO_2[b]	Background	
West Border (Fence) Core S-2	08/03/83 08/03/83	Benzene SO_2	Background Background	
West Border (Fence) Core S-3	08/05/83 08/05/83	Benzene SO_2	0.35 0.12	<5 minutes
West Border (Fence) Core N-1	08/08/83 08/08/83	Benzene SO_2	0.12^c Background	
West Border (Fence) Core N-2	08/09/83 08/09/83	Benzene SO_2	0.16^c Background	

[a] Benzene instrument (HNU) background typically 0.1 ppmv.

[b] SO_2 instrument (Interscan Analyzer) background typically 0.05 ppmv.

[c] Reading attributed to instrument drift.

[d] Background refers to instrument reading in "clean" air.

TABLE 22. SUMMARY OF DOWNHOLE EMISSIONS DATA

		SO_2 (ug/m^2 min^{-1})		THC (ug/$m^2 min^{-1}$)	
Core	Depth (ft)	Peak	Steady[b] State	Peak	Steady[b] State
S-1	5	$<1.9E^4$	$7.2E^3$	$1.6E^2$	$3.8E^1$
	7-1/2	$>1.1E^4$	$3.8E^3$	$1.3E^4$	$6.8E^3$
	15	$2.2E^3$	$\leq 8.3E^2$	$>3.8E^4$	$6.8E^1$
Average			$3.9E^3$		$2.3E^3$
S-2	2-1/2	$1.1E^4$	$5.4E^3$	$1.9E^3$	3.83^1
	4-1/2	$6.0E^3$	$1.9E^3$	$8.3E^3$	$3.8E^1$
	15	$2.5E^3$	$1.7E^3$	$>3.8E^4$	$9.5E^1$
	20[a]	$>1.1E^4$	$>1.1E^4$	$>3.8E^4$	$>3.8E^4$
	20	$4.0E^3$	$2.9E^3$	$>3.8E^4$	$3.8E^2$
Average			$4.6E^3$		$9.3E^5$
S-3	5	$1.6E^2$	$1.6E^2$	$4.6E^2$	$7.6E^1$
	10	$4.6E^2$	$4.6E^2$	$>3.8E^4$	$>3.8E^4$
	15	$7.6E^2$	$4.6E^2$	$1.6E^4$	$7.6E^3$
	20	$3.0E^2$	$1.6E^2$	$>3.8E^4$	$2.3E^2$
	30	$6.0E^2$	$1.6E^2$	$>3.8E^4$	$6.0E^2$
Average			$2.3E^2$		$9.3E^5$
N-1	5	$1.1E^3$	$1.6E^2$	$>3.8E^4$	$3.8E^2$
	10	$1.7E^3$	$1.7E^3$	$1.1E^4$	$8.8E^2$
	15	$9.7E^2$	$7.6E^2$	$2.3E^4$	$2.0E^2$
	25	$1.1E^3$	$7.6E^2$	$>3.8E^4$	$2.9E^2$
Average			$8.5E^2$		$4.4E^2$
N-2	10	$1.6E^3$	$1.3E^3$	$>3.8E^4$	$5.6E^3$
	20	$6.7E^2$	$6.8E^2$	$>3.8E^4$	$2.6E^2$
Average			$9.9E^2$		$2.9E^2$

[a] Range of emissions, two measurements were conducted.

[b] Steady-state values were averaged by core by operable unit to determine BEEs.

E = Exponential Notation ($7.2E^3 = 7.2 \times 10^3 = 7200$).

Hydrocarbon Class	Average %	Range %[a]
Alkanes	79.0	68 - 87
Alkenes	15.0	0.87 - 21
Aromatics	4.2	2.4 - 8.1
Oxygenates	0.62	0.15 - 1.5
Halogenated	1.2	0.091- 3.3
Sulfonated	ND	ND
Unidentified	2.0	0.42 - 6.6

[a] 5 cores, 6 canister samples

These data show that most of the air emissions were alkane species and of no significant concern regarding toxicity. The aromatic fraction was, as expected, around 5 percent, and was composed of numerous compounds.

5.1.7 Development of BEEs

Calculation of baseline emission estimates (BEEs) can be developed from either ambient concentration data (indirect techniques) or from emission rate measurement data (direct techniques). BEEs can be calculated for each contaminant species detected or for a group of contaminant species. BEEs obtained from direct measurement techniques which provide rate data (i.e., mass per unit time per given surface area) are preferable. The BEE is normalized for the area of the source and has units of mass of contaminant or group of contaminants per time.

BEEs can be calculated from individual emission sources and summed for sites containing multiple emission sources (operable units), such as a lagoon and a landfill with each source characterized by different air emission rates and contaminant species.

The calculation of an undisturbed emission estimate for this site included the following considerations. The site consisted of a waste area containing a landfill in the northern portion and a lagoon in the southern portion, separated by a berm. Each portion of the site was evaluated separately. Undisturbed emission factors for each of the two operable units were calculated separately and then averaged to provide an overall site emission estimate. The undisturbed emission rates for the lagoon and the landfill, and the combined site emission estimate calculations are presented below.

The undisturbed BEE for the lagoon (average) was calculated for SO_2 and THC. The surface emission isolation flux chamber survey results from five single measurements were averaged by species and multiplied by the lagoon surface area to determine the unit BEE.

Lagoon BEE_{SO_2} = (1.2ug/m^2-min)(6860 m^2) = 8.2×10^3 ug/min of SO_2

Lagoon BEE_{THC} = (36 ug/m^2-min)(6860 m^2) = 2.5×10^5 ug/min of THC

Similarly, the BEE for the landfill operable unit (average) was calculated for SO_2 and THC. The emission isolation flux chamber survey results were averaged for each species and multiplied by the surface area of the landfill to determine the unit's BEE.

Landfill BEE_{SO_2} = (0.77 ug/m^2-min)(7240 m^2) = 5.6×10^3 ug/min of SO

Landfill BEE_{THC} = (18 ug/m^2-min)(7240 m^2) = 1.3×10^5 ug/min of THC

The overall site BEE (for SO_2 and THC) can be obtained by summing the respective unit BEEs by species.

Calculation of emission estimates for disturbed site conditions can be performed from either air monitoring data (concentration measurements) during waste disturbances or from direct emission rate measurement data. Concentration values can be expressed as a concentration (ppm-v) for each species, as a ratio of the species concentration to the total concentration from all species, or as a percentage value for the species of interest over the total concentration contributed from all other species. The disturbed site emission flux data has the units of mass per time per unit area.

The emission estimate is calculated by multiplying the average measured emission rate by the total surface area of disturbed material. This results in a single value of mass per unit time which provides a relative estimate of the rate of air emissions from the source. Emission estimates can be calculated for a site with either individual sources or with multiple sources. These operable units often are investigated and remediated independently. Emission estimates for a combined site can be calculated by using the highest disturbed emission estimates for each source and summing the emission per time for each source.

Summaries of the average disturbed emissions flux for both units of the Case Study 1 site are presented below:

Landfill

SO_2 = 9.2×10^2 (ug/m^2-min)

THC = 1.7×10^3 (ug/m^2-min)

Lagoon

SO_2 = 2.9 x 103 (ug/m^2-min)

THC = 6.4 x 103 (ug/m^2-min)

These data can be used in conjunction with estimates of exposed disturbed waste to predict air impacts from various waste disturbance and treatment techniques.

Example

Excavation of the landfill would typically expose 50 m^2 of waste at a time. The estimate of THC air emissions from the site activity would be:

$$\text{THC (landfill)} = 1.7 \times 10^3 \ (ug/m^2,\ minute^{-1}) \times 50m^2$$
$$= 8.5 \times 10^5 \ (ug/min)$$

Depth-specific information could be used to provide area and depth-specific emission estimates as needed.

5.1.8 Summary

The Case Study 1 investigation was generally a thorough, well documented study that fully addressed the air pathway for volatile contaminants. The study followed closely the steps outlined in this manual's protocol and all objectives were met. Furthermore, site personnel report that the knowledge of the potential for emissions, ultimately resulted in a safer and more cost-effective remediation of the site. BEEs were used in risk assessment and in designing removal plans. Air emission control techniques were selected based on the BEEs.

5.2 CASE STUDY 2: BRUIN LAGOON

Case Study 2 is a disposal lagoon that received various wastes from a mineral oil refinery. This site was under remediation in 1984 when subsurface gases were unexpectedly released during cleanup. Work was halted and the remedial design was reassessed. A second Remedial Investigation/Feasibility Study (RI/FS) was then performed. This case study focuses on the APA conducted during this second RI/FS (see Table 23).

5.2.1 Site History

Bruin Lagoon is located about 45 miles north of Pittsburgh, in Bruin Borough of Butler County, Pennsylvania. The 4-acre site is situated along the western bank of Bear Creek's South Branch, approximately 7 miles upstream of the creek's confluence with the Allegheny River. Part of the site lies within the creek's 100-year floodplain. To the west, the site is bordered by private homes and State Route 268. Bruin Borough's main residential and commercial areas are within five blocks of the site and more than 30 residences are within 500 feet of the lagoon. To the south is an abandoned refinery, which is the source of the wastes deposited in the lagoon. Also, adjacent to the site are two ponds and a small stream that drain into Bear Creek.

TABLE 23. APA ACTIVITIES CONDUCTED AT THE CASE STUDY #2 SITE

APA Objectives

Assess the extent and composition of subsurface gas pockets. Monitor the ambient air for health and safety reasons.

Scoping

Initially, the lagoon was determined to contain wastes that had minimal potential for volatile or particulate matter emissions (first RI/FS). The second RI/FS did assume that volatile emissions from subsurface gas pockets were likely.

Screening Measurements

A variety of portable, real-time analyzers and detector tubes were used to monitor the ambient air during drilling activities. Monitoring took place at the site perimeter and in the ambient breathing zone near the drill rig. Soil samples were collected and the emissions from the samples were scanned. The screening data were used to design the in-depth measurement strategy.

In-Depth Measurements

The in-depth emission measurements involved collecting and analyzing grab samples of gas from boring/wells whenever the ambient breathing zone monitoring showed elevated concentrations significantly over background levels. However, these data were not used to develop undisturbed and disturbed site BEEs.

Mitigation

The disturbed waste emissions data were used in the development of the remedial action plan. Although disturbed emission rates were not calculated, knowledge of areas considered to be "hot spots" were used to conduct site operations in a way that prevented major releases of air toxics to the air. The remedial alternative included gas monitoring during on-site stabilization and neutralization of the unstabilized sludge and collecting, venting, and treating as necessary.

Currently in remediation, Bruin Lagoon is an unlined earthen diked lagoon that has been partially covered with 9300 cubic yards of stabilized soil/sludge mixture treated during the first attempt at remediation. Beneath this material is approximately 17,200 cubic yards of unstabilized sludge/tar, with up-welling of the waste in a number of areas. The sludge/tar contains sulfuric acid and heavy metals, along with other contaminants. The lagoon area of the site is generally level and lacks vegetation. A cross-sectional view of the site is shown in Figure 24.

Bruin Oil Company, producer of white (mineral) oil, began disposing of its wastes at the lagoon in the 1930s. This continued for more than 40 years. Materials discarded there included:

- Residues scraped from crude oil storage tanks;
- Used bauxite, charcoal filtering agents, and bone powder;
- Oils not meeting specification;
- Coal fines;
- Lime;
- Spent alkali; and
- Boiler house coal and ashes.

The lagoon attracted national attention in 1968 when about 3,000 gallons of acidic sludge spilled into the South Branch of Bear Creek through a breach in the dike. In the Allegheny River, roughly 4 million fish died and many downstream communities temporarily lost their water supplies. The spill was addressed, but the remedial investigation of the site didn't begin until 1981.

The abandoned refinery and the lagoon were owned by AH & RS Coal Company, which underwent bankruptcy proceeding in 1986.

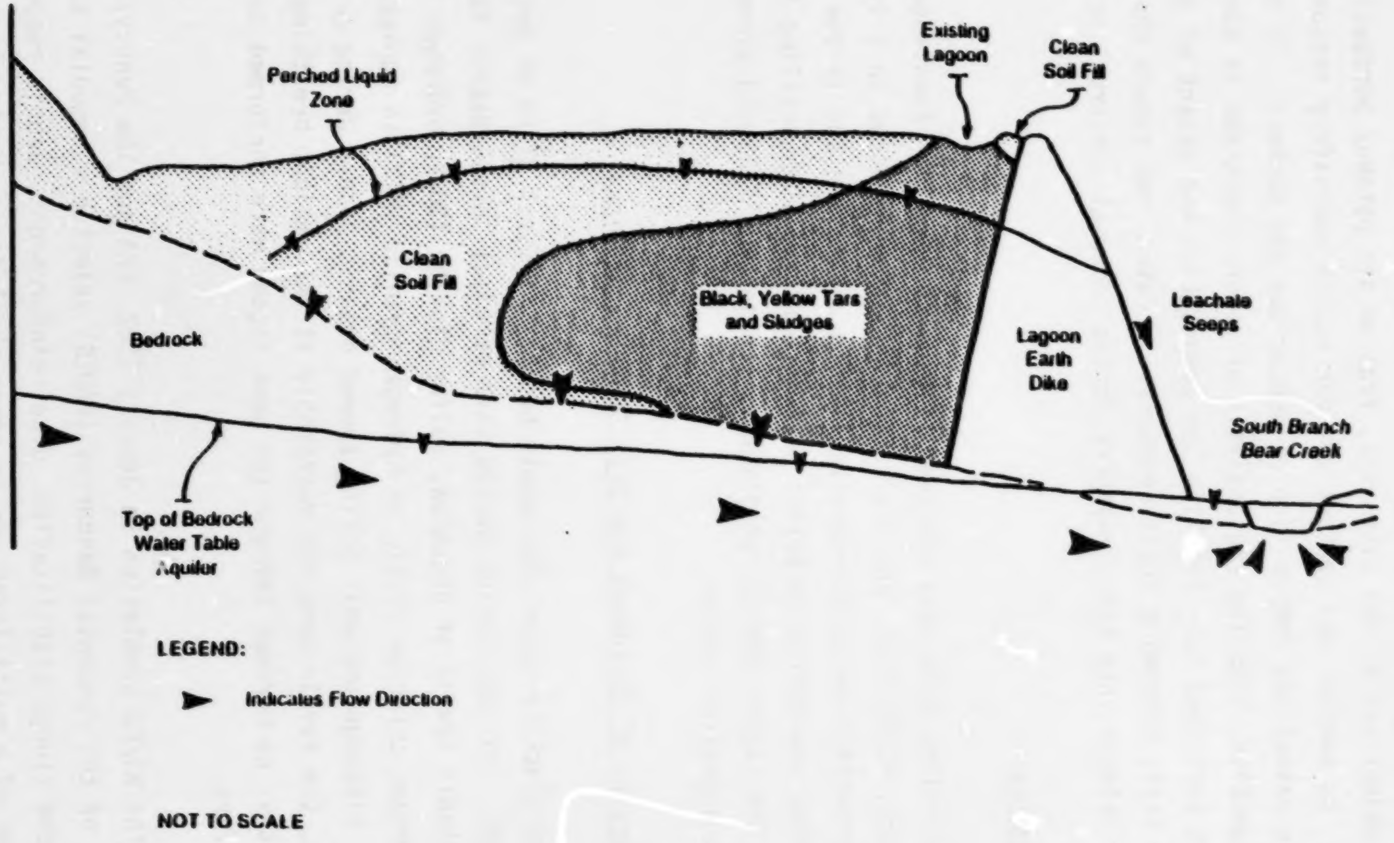

Perched Liquid Zone
Existing Lagoon
Clean Soil Fill
Clean Soil Fill
Black, Yellow Tars and Sludges
Leachate Seeps
Lagoon Earth Dike
Bedrock
South Branch Bear Creek
Top of Bedrock Water Table Aquifer
LEGEND:
Indicates Flow Direction
NOT TO SCALE

Figure 24. Generalized flow regime of perched zone and bedrock aquifer.

5.2.2 Objectives

The objectives of the site work, from an air pathway perspective, were two-fold: to monitor the ambient air for health and safety reasons; and to assess the extent and composition of subsurface gas pockets. To meet the latter objective, sampling and analysis of vapors contained in the shallow wells were performed to: identify the composition and extent of gases trapped under the site; determine their regeneration rates; and assess the potential for their release into the atmosphere during remedial construction work.

5.2.3 Scoping

The existing data were reviewed to provide a working knowledge of the site history, conditions, and environmental setting. Based on this review, no specific potential emission characterization was called for in the first RI/FS. After unexpected emissions were encountered when drilling through the bottom of the lagoon during remediation, the second RI/FS did address the air pathway to a greater extent.

5.2.4 Overview of Fieldwork For Site Characterization

EPA contractors began what would become the first RI/FS at Bruin Lagoon in July 1981. Air monitoring during this remedial investigation failed to find detectable levels of organics, sulfur dioxide (SO_2), hydrogen sulfide (H_2S), hydrogen chloride (HCl), or hydrogen cyanide (HCN) in ambient air at the site. Although one well boring showed organic vapors during drilling operations, the levels were not detectable at the ambient breathing zone. Significantly, no borings through the open lagoon were performed in this initial effort.

With the RI/FS completion in January 1982, EPA and the Pennsylvania Department of Environmental Resources (PADER) selected a remedial alternative that included sludge stabilization, dike reinforcement, debris removal, and construction of a multi-layer cap to cover the lagoon. Design kicked off in September 1982 and cleanup actually started in August 1983.

The project proceeded until May 4, 1984, when hazardous gas and acid mist escaped from an unanticipated crust, thought to be the bottom of the lagoon, that was broken during mitigation. These organic vapors and sulfur dioxide or hydrogen sulfide reached the ambient breathing zone but were not detectable at the site perimeter. Gas sampling was performed for worker and public protection. Gas samples from beneath the crust revealed high concentrations of carbon dioxide, hydrogen sulfide, and sulfuric acid mist. Consequently, EPA suspended cleanup activities and immediately launched in emergency response, which included some removal, covering the lagoon with stabilized sludge, installing 13 shallow gas monitoring wells, and collecting and analyzing additional sludge and soil samples.

The site remained in the emergency mode until September 1984. The second RI/FS was initiated the following January. Air monitoring conducted throughout this RI included:

- Health and safety;
- Site perimeter;
- Ambient breathing zone;
- Downhole concentration sampling and analysis; and
- Sample screening.

Conclusions drawn from a review of all of these activities (the two RI/FS endeavors and the emergency action) included identification of a "hot spot" in the unstabilized portion of the lagoon that contained carbon dioxide, hydrogen sulfide, sulfur dioxide and methane at levels deserving attention during remediation. The RI/FS concluded, however, that subsurface gases were not present throughout the site. To address the "hot spot" the remedial alternative selected in September 1986 included gas monitoring, venting, and treating during excavation, followed by post-closure monitoring.

5.2.5 Undisturbed Emissions Survey

Based on the available documentation, no screening or in-depth measurements were made to assess the undisturbed emission at the site. Since the site contains heavy metals and is unvegetated, an evaluation of the entrained particulate matter from the site would have been advisable, and some screening measurements for particulates and inorganic gases may have been warranted. Some air monitoring was performed immediately prior to site disturbances. These limited data do address undisturbed emissions.

5.2.6 Disturbed Emissions Survey

Both screening (air monitoring and sample headspace) and in-depth (soil vapor well) measurement techniques were used to assess the emissions during site disturbances such as drilling. The following discussions are largely taken from the second RI/FS prepared for the Bruin Lagoon site (65).

Screening Measurements--

The following air monitoring equipment was available on site during all drilling activities:

- HNU photoionization detector (PID) with 11.7 and 10.2 eV probes;
- OVA (organic vapor analyzer) flame ionization detector (FID);
- H2S portable gas monitor;
- SO_2 portable gas monitor;
- H_2S monitor alarms;
- Explosimeter/oxygen monitor; and
- Detector tubes SO_2, H_2S, H_2SO_4, O_2, CO_2, natural gas.

Based on gases detected in past site work, portable direct reading real-time instrumentation was primarily used for gas characterization and health and safety purposes. Detector tubes were used for screening of possible instrumentation interferences, confirmation of direct reading concentrations, and analysis of gases not detected on available instrumentation.

The direct reading monitoring instruments determined to be most effective for monitoring drilling operations were the HNU PID (11.7 eV), H_2S portable gas monitor, H_2S monitor alarms, and SO_2 portable gas monitor. The HNU PID was selected over the OVA FID due to the sensitivity of this instrument to hydrogen sulfide gas. The HNU PID could detect both hydrogen sulfide gas and organic vapors. This selection was made because of past historical data demonstrating possible H_2S gas release.

Periodic monitoring of ambient air at the site perimeter was routinely performed during drilling operations. Also, if ambient breathing zone concentrations indicated possible gas releases, perimeter monitoring was immediately initiated. Seventeen monitoring locations were established along the site fence line at intervals of approximately 150 feet and marked with stakes. Figure 25 shows the perimeter monitoring locations. Perimeter monitoring was conducted with the H_2S and SO_2 portable gas monitors and the HNU PID.

During all drilling operations, the H_2S and SO_2 portable gas monitor, H_2S monitor alarms, explosimeter/oxygen monitors, and HNU PID were used for characterization of the ambient breathing zone. Background levels were determined prior to starting the drilling.

Portable instrument readings provided continuous, real-time monitoring of each split spoon and drilling depth to determine at what depth, if any, gas releases occurred. Each split spoon and core sample was scanned with Figure 25 all direct reading instrumentation immediately after collection. Samples showing positive readings were usually selected for chemical analysis.

In-Depth Measurements--

If ambient breathing zone monitoring showed elevated concentrations significantly above background levels, a grab sample of the gas present in the boring/well was collected for analysis. These grab samples were analyzed to characterize the emitted gases. Grab samples were collected from a point approximately 3 feet below the ground surface by inserting tubing into the

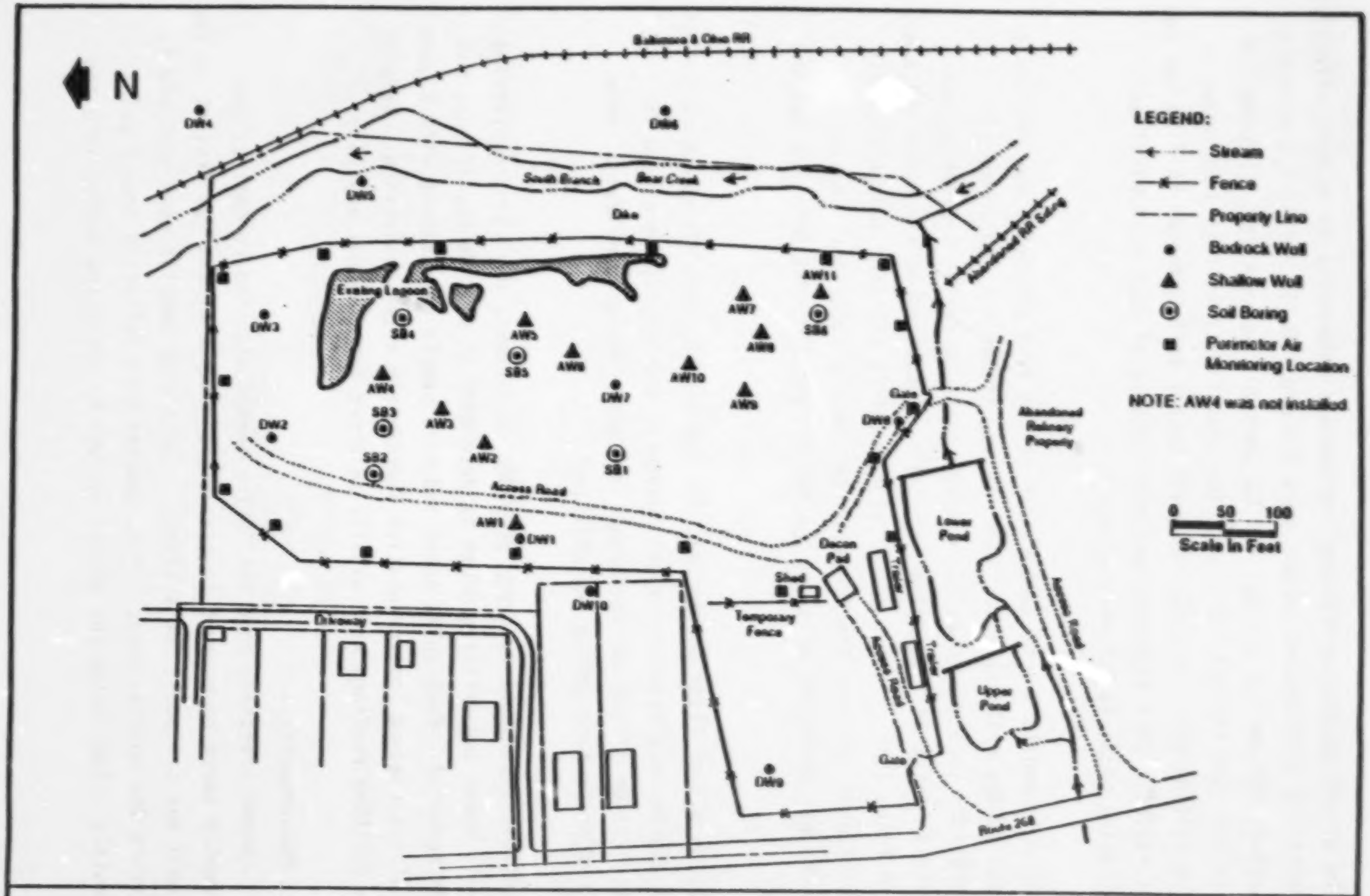

N
Baltimore & Ohio RR
DW4
DW6
DW5
South Branch
Bear Creek
Dike
Abandoned RR Siding
Existing Lagoon
AW11
AW7
SB6
AW8
AW5
AW6
AW10
AW9
DW3
SB4
SB5
AW4
DW7
Gate
DW8
SB3
AW3
DW2
AW2
SB1
SB2
Access Road
AW1
DW1
Abandoned Refinery Property
Lower Pond
Decon Pad
Trailer
Shed
Temporary Fence
DW10
Driveway
Access Road
Upper Pond
DW9
Gate
Route 268
LEGEND:
Stream
Fence
Property Line
Bedrock Well
Shallow Well
Soil Boring
Perimeter Air Monitoring Location
NOTE: AW4 was not installed
0
50
100
Scale in Feet

Figure 25. Monitor well and soil boring locations at the Bruin Lagoon site.

boring/well and pumping the gas into an air bag collector. The bag sample was then sealed and analyzed on-site using available instrumentation and detector tubes.

Disturbed Emission Survey Results--

The following results are taken from the second RI/FS prepared for the Bruin Lagoon site (65).

Air monitoring conducted during the 1981 remedial investigation of Bruin Lagoon revealed no detectable levels of organics, SO_2, H_2S, HCl, or HCN in the ambient air at the site. Organic vapors were detected within one well boring during drilling operations; however, no detectable levels were found in the ambient breathing zone at this location. It should be noted that no borings were constructed through the open lagoon during the initial RI and, as a result, the gases trapped below the crust were not encountered.

Background air monitoring performed during field work in June 1984 showed no detectable levels of H_2S or methane. Air samples collected from the soil boring indicated the presence of H_2S, CO_2, methane, and aromatic hydrocarbons. SO_2 was not detected in the downhole samples. H_2S was present in the soil gas on the average at about 300 to 400 ppm; initial concentrations were greater by an order of magnitude or more.

Low levels of organic vapors, sulfur dioxide and hydrogen sulfide were released into the ambient breathing zone when the subsurface of the site was disturbed by drilling operations. SO_2 concentrations were observed as high as 50 ppmv but typically were found at 0.5 to 18 ppmv in the breathing zone during drilling operations. H_2S concentrations were lower with high concentrations observed at 14 ppmv with typical concentrations of 1 to 10 ppmv. However, concentrations of these gases were not detectable at the site perimeter.

The analytical results for the subsurface gas samples collected from the 13 shallow wells installed during the 1984 emergency action showed various concentrations of volatile organics, SO_2, H_2SO_4, and methane in the wells.

Methane was observed in all the wells ranging from 2.6 to 4,400 ppm. These concentrations showed good correlation with the organic CH_4 levels measured in the field by the OVA. Analysis of carbon tube samples collected for each well showed no detectable volatile organic compounds. Sulfur dioxide was found to be present in 11 of the 13 wells, with four wells having SO_2 concentrations greater than 100 ppm.

The results of the 1984 sampling of subsurface gases at the Bruin Lagoon site showed elevated levels of SO_2. The presence of H_2SO_4 mist was limited to three wells (A-8, A-10, and A-13). Additionally, reactions and gas releases occurred during the installation of each of these wells. Elevated levels of SO_2 also were detected in well A-2. These wells are all located within 50 feet of one another, and, as a result, the data suggest that this area of the site is a "hot spot" with respect to potentially harmful trapped subsurface gases. Additional sampling one year later confirmed the presence of a "hot spot" area located in the central part of the site.

5.2.7 Development of BEEs

No baseline emission estimates or disturbed emission estimates were generated. It was noted, however, that remediation may result in the release of pockets of hazardous gases trapped below a crust at the bottom of the lagoon. BEEs would allow performance of risk assessments for various release and meteorological scenarios at receptor points of interest.

Given the available data, the best method for determining BEEs for this site would be to take the existing ambient air monitoring data and back-calculate an emission rate using an air dispersion model. This is done by setting up the model's run conditions to match those at the site as closely as possible, and then varying the source term to find an emission rate that produces downwind concentrations equal to those actually measured. Using the respective air monitoring data sets, this procedure could be used for both undisturbed and disturbed conditions. However, the accuracy of this procedure is limited by the amount and representativeness of the available air monitoring data.

5.2.8 Summary

The Case Study 2 investigation points up the need to consider potential emissions from the disturbed site before any remedial actions are undertaken. Here, no soil borings through the open lagoon were performed during the first RI/FS. The initial failure to do so, or to even consider potential air emissions at this site, resulted in the need for a second RI/FS and associated schedule delays and extra expenses. The study did not closely conform to the steps outlined in the protocol of this manual. No undisturbed emission measurements were performed (beyond some background air monitoring) and no emission rate data were collected.

The best technique for screening particulate matter (PM) emissions at this site would have been to collect upwind/downwind samples on filters using high-volume sampling pumps (hi-vols). The total particulate matter present in the air would be determined by dividing the filter weight gain by the volume of air sampled. Analysis of the filter catch for selected metal species would assist in assessing the health impacts from undisturbed emissions. A less acceptable alternative would have been to measure the ambient particulate matter loadings using a portable particulate matter analyzer. The activities conducted, however, provided valuable data that were very useful in the design, selection, and implementation of the remedial alternative.

5.3 CASE STUDY 3: LOWRY LANDFILL

Case Study 3 is an active municipal landfill that formerly also accepted liquid and solid industrial wastes and domestic sewage sludge. This case study focuses on APA activities conducted at the site (see Table 24).

5.3.1 Site History

The Lowry Landfill is co-owned by the City and County of Denver, Colorado. It opened for business as a municipal landfill in 1965. The site is located about 20 miles southeast of Denver and two miles east of the City

TABLE 24. APA ACTIVITIES CONDUCTED AT THE CASE STUDY #3 SITE

APA Objectives

A soil gas study was conducted to locate waste pits, determine the extent of off-site subsurface gas migration, and determine the waste pit contribution to such migration. An air monitoring program was conducted to measure ambient air pollutants during installation of monitoring wells in the waste pits.

Scoping

The landfill was determined to contain both hazardous and municipal wastes. The generation of off-gases from the wastes was considered to be a hgih probability.

Screening Measurements

The ambient air was monitored upwind and downwind of the site during monitoring well installation. Samples were collected using a variety of adsorption media. Soil samples were collected and the emissions from the samples were scanned.

In-Depth Measurements

The in-depth emission measurements involved collection of soil gas samples at a large number of points using vapor monitoring wells for deep samplign and ground probes for shallow sampling. However, these data were not used to develop undisturbed and disturbed site BEEs.

Mitigation

Migration plans have not yet been prepared. The site is currently under study to further understand the air emissions potential from the site. These study activites include air monitoring at nearby receptors of concern (e.g., community school).

of Aurora, in Arapahoe County. The site covers approximately 480 acres. The surrounding area was mostly undeveloped when the landfill was established, but is growing rapidly today. (Proximity of the closest residence was not given in the Remedial Investigation (RI) report.

From 1965 until the advent of the Resource Conservation and Recovery Act (RCRA) in 1980, the facility accepted municipal refuse, liquid and solid industrial waste (some of which was hazardous), and domestic sewage sludge. The landfill handled these wastes by excavating pits, filling them three-quarters with liquids and then covering the waste with refuse until a mound several feet above the land surface was created. Landfills were dug repeatedly, sometimes into old, filled landfills. The landfills at the south end of the facility were covered with as much as 30 to 60 feet of refuse.

In 1975, Continental Oil Company contracted with site owners to set up and run an oil sludge disposal operation in the southeastern portion of the site. This operation and the acceptance of industrial waste stopped with RCRA in 1980. At that time, the City and County of Denver hired a private firm to manage the site as a municipal waste facility only. This contractor, Waste Management, Inc., formed a subsidiary which opened a hazardous waste disposal facility just north of Lowry. This facility was closed in 1982.

In the early 1980s, Lowry Landfill began to be closely scrutinized by a number of public agencies due to odor problems and other concerns. These first cursory looks focused primarily on the groundwater contamination pathway, studying only shallow groundwater. Not all landfills were located or confirmed. Initial investigations disclosed that records of types and locations of waste were incomplete and inaccurate. Also, no measures had been taken to prevent leachate or seepage from these pits.

Among the 60 pits identified through aerial photographs, it was estimated that roughly 100 million gallons of liquid wastes were disposed on-site over 15 years. Wastes identified include: acid and alkaline sludges; caustics and solids; brines, including plating wastes and other water-based sludges; organics, both natural and synthetic, such as petroleum-based oils, grease, and chlorinated solvents and sludges; watersoluble oils; municipal sewage sludge; low-level radioactive wastes; pesticide wastes; asbestos; and metallic wastes.

EPA did not become intimately involved at the site until about 1981 when Lowry was first considered as a candidate for the NPL. In 1984, Lowry was placed on the NPL and formal investigations were initiated.

5.3.2 Objectives

At the Lowry site, a soil gas study and an air quality investigation were performed as part of the RI. The soil gas study was conducted to help locate the waste pits, to determine the extent of any off-site subsurface migration, and to determine the waste pit contribution to such migration. The air quality investigation was conducted to measure contaminants in the ambient air during installation of monitoring wells in the waste pits.

5.3.3 Scoping

Existing data were collected and reviewed to provide a working knowledge of the site history, conditions, and environmental setting. A topographic map of the site and its environs was developed from aerial photos. Surveying was performed to map sampling locations and determine the relative coordinates and elevation of each location.

5.3.4 Overview of Fieldwork For Site Characterization

The purpose of the first phase, of a two-phase remedial investigation, was to characterize the site geology and climate; identify the location and contents of all landfills; characterize the extent of contamination, including air and soil gas; and identify data gaps to be filled in during rememdial investigation Phase II.

Investigatory work into some of the landfills was thwarted by three piles of vehicle tires, two piles of roughly 2 million tires each and one pile of up to 8 million tires. Findings disclosed that soil gas, air, groundwater, surface water, and soil all were contaminated and that some migration was occurring. To detect air contamination, contractors sampled upwind and downwind of the site, and 50 feet downwind from the five waste pit wells shortly after installation (to demonstrate a worst-case emissions scenario). The results showed that air quality was degraded as it crossed the site from south to north (the direction of the prevailing wind). Volatile organic compounds (VOCs) were detected at 0.020 to 16 parts per billion (ppb) higher in the downwind samples relative to the upwind samples.

Separately, samples for soil gas emissions were taken from the landfills, from gas well points and probes, and from 10 gas sampling wells installed around the site perimeter by the contracted facility operator in 1981. The results disclosed 19 VOCs, found in ranges of 37 to 160,000 ppb, and verified that contaminated soil gas was migrating off-site in the vicinity of one of the perimeter wells.

A complete meteorological monitoring station has been operating at Lowry since April 21, 1985. It measures wind speed and direction, temperature, relative humidity, barometric pressure, and precipitation on a 10-meter tower. Measurements are taken by a Climatronics Electronic Weather Station (EWS) connected to a Campbell Scientific CR21 data logger. The data are read periodically into a mainframe DEC-10 computer.

5.3.5 Undisturbed Emissions Survey

No screening or in-depth measurements were made to assess the undisturbed emissions at the site. However, the Phase I RI report (66) does recommend that ambient air and meteorological monitoring be performed in the planned Phase II work to collect background data. Based on the types of waste present and the presence of contaminated soil gas, screening measurements (at a minimum) would have been warranted for this site during Phase I activities.

5.3.6 Disturbed Emissions Survey

Both screening (headspace sampling and upwind/downwind air monitoring) and in-depth (soil vapor wells) measurement techniques were used to assess the air pathway.

Screening Measurements--

Split spoon samples collected during drilling activities were retrieved and opened, then the air space above the samples was scanned using an HNU portable organic vapor analyzer.

The ambient air was monitored over a 12-day period during installation of monitoring wells in the waste pits. The monitoring took place in November and December of 1985 during which there was some snow cover; therefore, the results do not equal a worst-case scenario. Samples were collected upwind and downwind of the site and 50 feet downwind of the waste pit well installations. A controlled release of waste pit well gas was permitted to help predict ambient air impacts associated with remediation of the waste pits. Samples were collected by concentrating air on carbon molecular sieves (CMS), polyurethane foam, Tenax, and glass fiber filters. The sampling methods are listed in Table 25.

In-Depth Measurements--

Soil gas samples were collected from a number of locations, including 10 existing soil vapor wells around the perimeter of the facility and wells installed at four locations in suspected waste pits. The wells at the waste pits were drilled to within 2 feet of the water table. Ground probes also were driven into the waste pits at the same four locations to measure the gas emanating from the waste pits and municipal refuse and reaching the near-surface. Three more ground probes were installed at areas without underlying waste pits.

Samples were collected from all locations using a pump to transfer gas to a tedlar bag within a rigid-wall container. Sample gas was extracted at roughly 1 L/min for 4 to 5 minutes. The perimeter soil vapor wells required purging (three well volumes) before sample collection; the other sampling points had free-flowing gas.

Samples were analyzed for priority pollutants by GC/MS using EPA Method 624 at an off-site location.

TABLE 25. SUMMARY OF AIR MONITORING AT LOWRY LANDFILL

Collection Media	Equipment Description	Number of Samples	Analytes	Duration of Sampling (Hours)	Method of Analysis
Tenax	Gillian HFS personal pumps	52	Highly Volatile Organic Compounds	8-12	GC/MS (Method TO-1)
Carbon Molecular Sieve	Gillian HFS personal pumps	52	VOCs	8-12	GC/MS (Method TO-2)
Glass Fiber Filters	Sierra Accu-Vol high-volume samplers	20	TSP[a], Metals	8-12	EPA Reference Methods
Polyurethane Foam (PUF)	GMW Model PS-1 high-volume samplers	26	Semi-volatiles and Pesticides/PCBs	8-12	GC/MS (Method 625 and Method TO-4)
N/A	Climatronics Wind Mark III	Continued	Met Data	N/A	N/A

[a] Total suspended particulate matter.

Disturbed Emission Survey Results--

A large data base was developed during this program and is summarized here.

The upwind/downwind sampling indicated that the site is a VOC emissions source. Total VOCs on-site were 54 ppb higher than upwind values, and downwind concentrations were 25 ppb higher than upwind values. Downwind concentrations of acetone, carbon disulfide, and toluene were 3 to 10 times the upwind values. During the controlled release, these compounds were found at 8 to 100 times the upwind values. Other compounds, such as 1,1,1-trichloroethane, benzene, and TCE also were found at elevated (4 to 20 times) levels downwind. These emissions could be expected to be greatly higher during non-winter weather conditions.

The upwind/downwind sampling showed particulate matter emissions to be a problem at the site. The upwind values averaged 187 ug/m^3 and the downwind samples averaged 325 ug/m^3 with a range of 112 to 643 ug/m^3. The average downwind total solid particulates (TSP) exceeded the Primary TSP National Ambient Air Quality Standard of 260 ug/m^3.

Nineteen hazardous volatile organic compounds were detected in soil gas samples emanating from waste pit liquid. These compounds were similar to those found in the liquid samples. Concentrations ranged from 460 to 291,000 ppb. Nineteen volatile organic compounds were found in the refuse gas samples, in ranges of 37 to 160,000 ppb. Compounds were nearly identical to those found in gas samples above waste pit liquids except that the concentration of compounds above these liquids was two to five times greater than in the overlying refuse and six times greater than in refuse with no underlying pits. It is reasonable to conclude that the liquids and refuse are contributing to gas contamination.

The results of perimeter well gas sampling indicate that subsurface contaminant migration has occurred at Well GPM-3 and possibly at GPM-7. Thirteen hazardous substances were detected in gases at Well GMP-3, near waste pits and refuse disposal areas. Substances included volatile organics at ranges of 9 to 1,200 ppb.

5.3.7 Development of BEEs

No baseline emission estimates for either the undisturbed or disturbed wastes were generated, though sufficient data exist to estimate a disturbed BEE. Given the available data, the best method for determining BEEs for this site would be to take the existing ambient air monitoring data and back-calculate an emission rate using an air dispersion model. This is done by setting up the model's run conditions to match those at the site as closely as possible, and then varying the source term to find an emission rate that produces downwind concentrations equal to those actually measured. Using the respective air monitoring data sets, this procedure could be applied to both undisturbed and disturbed conditions.

5.3.8 Summary

The Case Study 3 investigation did not closely conform to the protocol steps outlined in this manual. No undisturbed emission measurements were performed and no emission rate data were collected. While substantial data were collected, scheduling the air monitoring during cold temperatures and snow cover conditions limited the data's applicability.

The best technique for screening undisturbed emissions at this site would be to: 1) perform ambient air monitoring around the perimeter of the facility to determine the magnitude of baseline emissions from the site and to verify if any adverse health or safety risks are present; and 2) survey the site using a portable analyzer and windscreen to delineate any localized emission "hot spots." The results of these screening studies would need to be interpreted to determine if any further undisturbed emission measurements were warranted.

5.4 CASE STUDY 4: WESTERN PROCESSING LANDFILL

Case Study 4 is a former industrial waste processing and recycling facility.

5.4.1 Site History

The 13-acre Western Processing site is situated in the Green River Valley between Seattle and Tacoma, five miles inland from Puget Sound. The site was used for agricultural purposes until 1951 when it was leased to the Department of Defense. An anti-aircraft artillery base operated there until the lease expired in 1960. The owner opted for a cash settlement and left in place the installation's buildings and on-site drainage system that linked its facilities to a septic tank, a tile subsurface drain field, a 500-gallon chlorination tank and a ditch leading to Mill Creek which runs along the site's western border.

Western Processing, a waste recycling operation, purchased the site in 1960 and claimed to have reclaimed or recycled millions of gallons of liquid waste and thousands of tons of solid waste before it was shut down in 1982. The wastes handled included: animal blood, brewer's yeast, chrome baths, corrosive liquids, crank case oil, flue dust, lead, pickle liquor, plating bath solutions, solvents and paints, and zinc skimmings. These wastes were handled, stored, or disposed of in storage lagoons (acid/caustic/cyanide wastes), a fertilizer plant, a solvent recovery plant, bulk storage tanks, cooling water lagoons, a chlorine gas tank storage house, a laboratory, naphtha storage tanks, a 55-gallon drum storage area, and piles of flue dust. By the late 1970s, the below-ground surface impoundments had been filled and were being used to store waste material.

The site is located in an industrial area. A barbed wire fence separates the site from a bicycle and jogging trail, which follows a railroad right-of-way. This is the nearest community exposure to the site. Trail users reported seeing hoses draped over the fence discharging into a ditch along the railroad tracks that feeds into Mill Creek, prior to the closure of the recycling plant (67). The site is shown in Figure 26.

5.4.2 Objectives

The Remedial Investigation/Feasibility Study (RI/FS) process did not address the air pathway for contaminant transport to any meaningful extent. Therefore, no objectives were set or met.

5.4.3 Overview of Fieldwork for Site Characterization

State and local inspections of Western Processing or its vicinity date back to 1977. These were initially concerned about the quality of water in Mill Creek. In 1982, EPA determined that the company's management practices were resulting in the release of priority pollutants and other contaminants to the environment.

A remedial investigation initiated in the fall of 1982 led to emergency and interim remedial site activities in April 1983. These included removal of some liquids, solids, and drums, and reorganization of concrete blocks from five surface impoundments to create a large diked area where excavated materials were then placed. The excavated materials contained solvents, paint sludge, and some heavy metals. Also, buried storage tanks and drums were encountered during this activity. Later in the fall, the state of Washington led an effort to prevent storm water infiltration and runoff, which included further excavation and berming as well as paving of the reaction pond.

A Phase I surface cleanup, funded by the potentially responsible parties, started with release of a remedial action plan (68) in July 1984. In that plan, it was clear that air emissions work had been limited. The report noted the northerly direction of winds would primarily deposit any contaminants stirred up or blown off waste piles in or near Puget Sound. The report cited a 1982 air analysis that showed only trace amounts of trichloroethene, toluene, xylene, and tetrachloroethene. The low levels and high volatility of these compounds, coupled with wide atmospheric dispersal, were thought to create only limited effects on receptors during past operations. "Although past releases into the atmosphere may have been greater than observed in the 1982 samples and undoubtedly included particulate matter and contaminants.

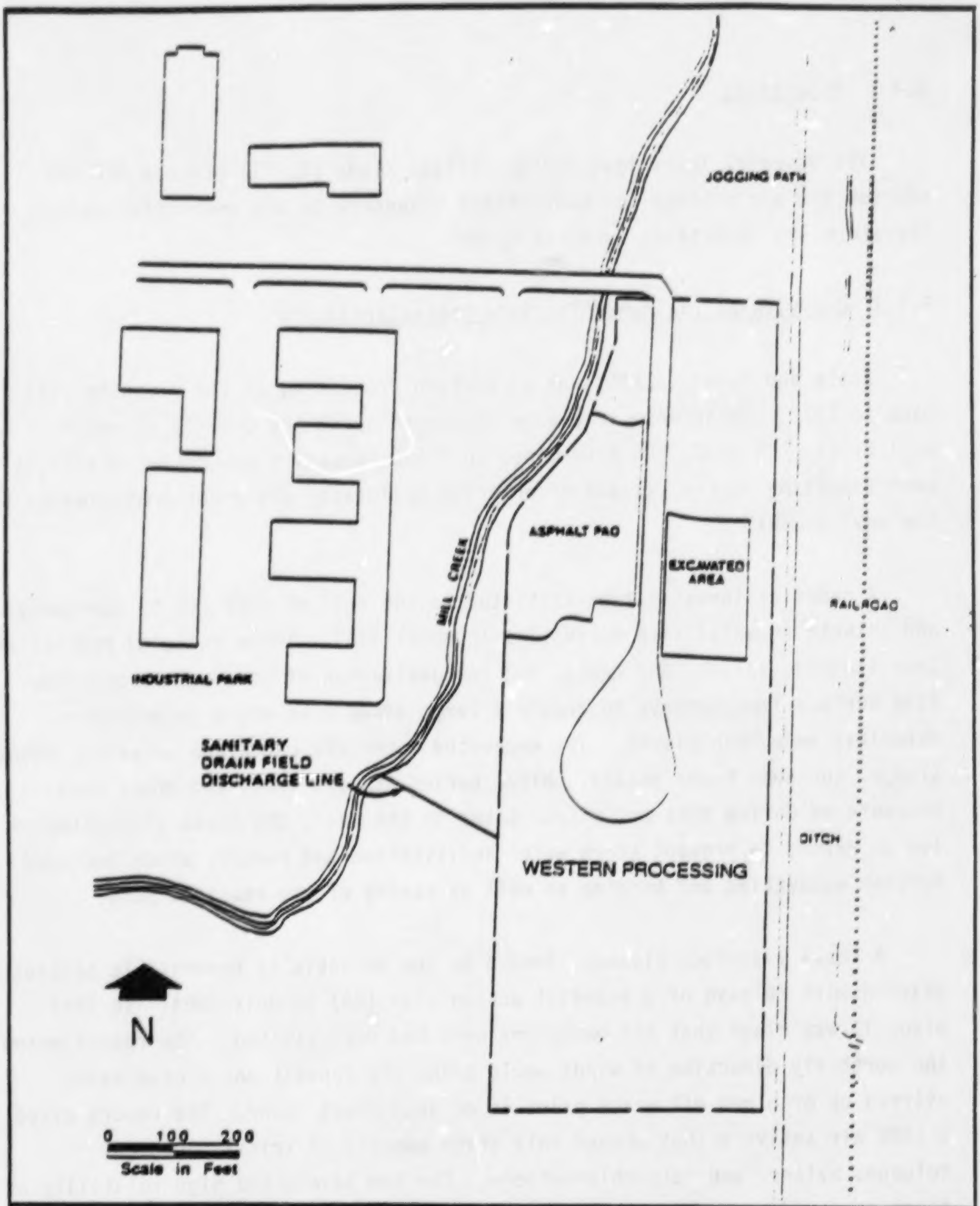

JOGGING PATH
ASPHALT PAD
EXCAVATED AREA
MILL CREEK
RAILROAD
INDUSTRIAL PARK
SANITARY
DRAIN FIELD
DISCHARGE LINE
DITCH
WESTERN PROCESSING
N
0 100 200
Scale in Feet

Figure 26. Western processing site.

Other than volatile organics, this pathway is not believed to have been significant."

That the air pathway was overlooked to some extent during the RI/FS stage is apparent. However, Phase II remediation work began in 1987 to remove shallow wastes at the site, and a comprehensive air monitoring program was initiated. This program is outlined below (as described in Lepic and Foster (69).)

An air monitoring program was implemented to ensure adequate protection of both the field team and the surrounding community. Work area monitoring was conducted to identify action levels where personnel protection levels must be upgraded. Continuous upwind and downwind perimeter monitoring was conducted.

Direct reading, real-time instruments were used to determine total gases and vapors, cyanide, gamma radiation and combustible gas; particulate concentrations also were measured. The field instrumentation used at Western Processing included:

- OVA 128: total organic vapors;
- HNU PI 101: total organic vapors;
- Hand-held aerosol monitor (HAM): total particulates;
- Gastech CGI: combustible gases;
- Ludlum 19: gamma radiation;
- Monitox Compur 4100: cyanide;
- Draeger pump and colorimetric detector tubes: cyanide and methane;
- Hi-volume air samplers: suspended particulates; and
- Recording meteorological station: wind direction and speed.

Air was monitored regularly at 16 fixed locations around the site perimeter to detect any possible off-site migration of airborne contaminants. In addition, monitoring was conducted at each sample location to determine adequate protection levels and to ensure worker safety. These monitoring procedures are described below:

- Borehole and excavation site monitoring: an OVA, HNU and HAM were used to monitor the breathing zone at the drill rig and backhoe during the subsurface exploration and sampling activities. A cyanide detector and combustible gas indicator were used regularly; and

- Drum, tank and utility monitoring: an OVA and HNU, radiation detector, combustible gas indicator and cyanide monitor were used to test the atmosphere within containers for flammable vapors.

5.4.4 Scoping

Collection and review of the existing data were performed. Based on this data review, no need for an air pathway analysis was perceived.

5.4.5 Undisturbed Emissions Survey

No screening or in-depth measurements were made to assess the undisturbed emissions at the site. Table 26 lists some of the contamination found at the site. Based on the very high concentrations of heavy metals (e.g., lead at 31,000 ppm) found in the surface soil, an evaluation of the entrained particulate matter from the site would have been advisable, and some screening measurements were warranted.

5.4.6 Disturbed Emissions Survey

No screening or in-depth measurements were made to assess the disturbed emissions at the site. Based on the very high concentrations of organic compounds in the subsoil, an evaluation of the emission potential would have been advisable.

TABLE 26. MAXIMUM AND AVERAGE CONCENTRATIONS IN SOIL FOR SELECTED CONTAMINANTS

Contaminant	Maximum Conc. (ppm) Surface	Maximum Conc. (ppm) Subsurface	Average[a] Conc. (ppm)
Chromium	5,300	7,600	594
Zinc	81,000	40,500	2,580
Arsenic	38	102	3.28
Antimony	98	130	8.59
Lead	31,000	141,000	5,450
Cyanide	15	179	11.2
Phenol	19.0	65.0	1.65
Aldrin	0	2.86	0.006
Dieldrin	0.145	3.34	0.007
PCB-1248	3.30	19.6	0.341
Hexachloroethane	5,090	1,80	0.0192
Phenanthrene	20,000	62.4	720
Pyrene	16,000	11.0	184
1,1,1-Trichloroethane	0	174	2.87
Methylene Chloride	0.130	49	1.49
Toluene	0	394	6.44
Trichloroethene	0.037	580	19.3

[a] Based on geometric averaging approach.

5.4.7 Development of BEEs

No baseline emission estimates for either the undisturbed or disturbed wastes were generated. Given the available data, the best method for determining BEEs for this site would be to take the existing ambient air monitoring data (discussed below) and back-calculate an emission rate using an air dispersion model. This is done by setting up the model's run conditions to match those at the site as closely as possible, and then varying the source term to find an emission rate that produces downwind concentrations equal to those actually measured. Using the respective air monitoring data sets, this procedure could be applied to both undisturbed and disturbed conditions.

5.4.8 Summary

The best technique for screening undisturbed particulate matter emissions at this site would have been to collect upwind/downwind samples on filters using high-volume sampling pumps (hi-vols). The total particulate matter present in the air would be determined by dividing the filter weight gain by the volume of air sampled. Analysis of the filter catch for selected metal species would assist in assessing the health impacts from undisturbed emissions. A less acceptable alternative would have been to measure the ambient particulate matter loadings using a portable particulate matter analyzer.

Screening VOC emissions also would have been advisable, based on the waste composition data. The best technique for screening undisturbed VOC emissions at this site would have been to: 1) perform ambient air monitoring around the perimeter of the facility to determine the magnitude of baseline emissions from the site and to verify if any adverse health or safety risks were present; and 2) survey the site using a portable analyzer and windscreen to delineate any localized emission "hot spots." The results of these screening studies would need to be interpreted to determine if further undisturbed emission measurements were warranted.

The best technique for assessing disturbed VOC emissions would have been to expose representative areas of waste using a backhoe (or drill rig), and to measure emission rates using the flux chamber technique. The best technique for assessing particulate matter emissions would have been to use hi-vol samplers arrayed downwind (i.e., transect technique) to capture emissions during site disturbances.

5.5 CASE STUDY 5: OUTBOARD MARINE CORP. LAGOON/LANDFILL

Case Study 5 is a manufacturing site where harbor sediments and nearby land are contaminated with PCBs.

5.5.1 Site History

Outboard Marine Corp. (OMC) sits on the west shore of Lake Michigan, 37 miles north of Chicago and 10 miles south of the Wisconsin border. This hazardous waste site evolved from an outboard motor manufacturer that used PCBs in die cast machines from the early 1950s to the early 1970s.

Over the years, the facility discharge created three areas of contamination (see Figure 27). The first is Waukegan Harbor, a 37-acre irregularly shaped harbor feeding into Lake Michigan. The operation also led to contamination of "North Ditch," a small tributary that drains surface water runoff into Lake Michigan. A nine-acre parking lot north of the plant was identified as another area of significant PCB contamination.

Concerns about possible receptors of site contamination included the harbor's biological community and fish in Lake Michigan. The City of Waukegan, population 67,653 in 1980, is nearby, but the harbor area is zoned industrial. The 15 businesses in the immediate harbor area that employ about 3,500 people were the immediate concern. Also, the local Port Harbor received heavy recreational use and long-term plans included development of the Upper Harbor. Potentially, people in a variety of locations could be exposed to the contamination via direct contact, fish consumption or possible drinking water contamination.

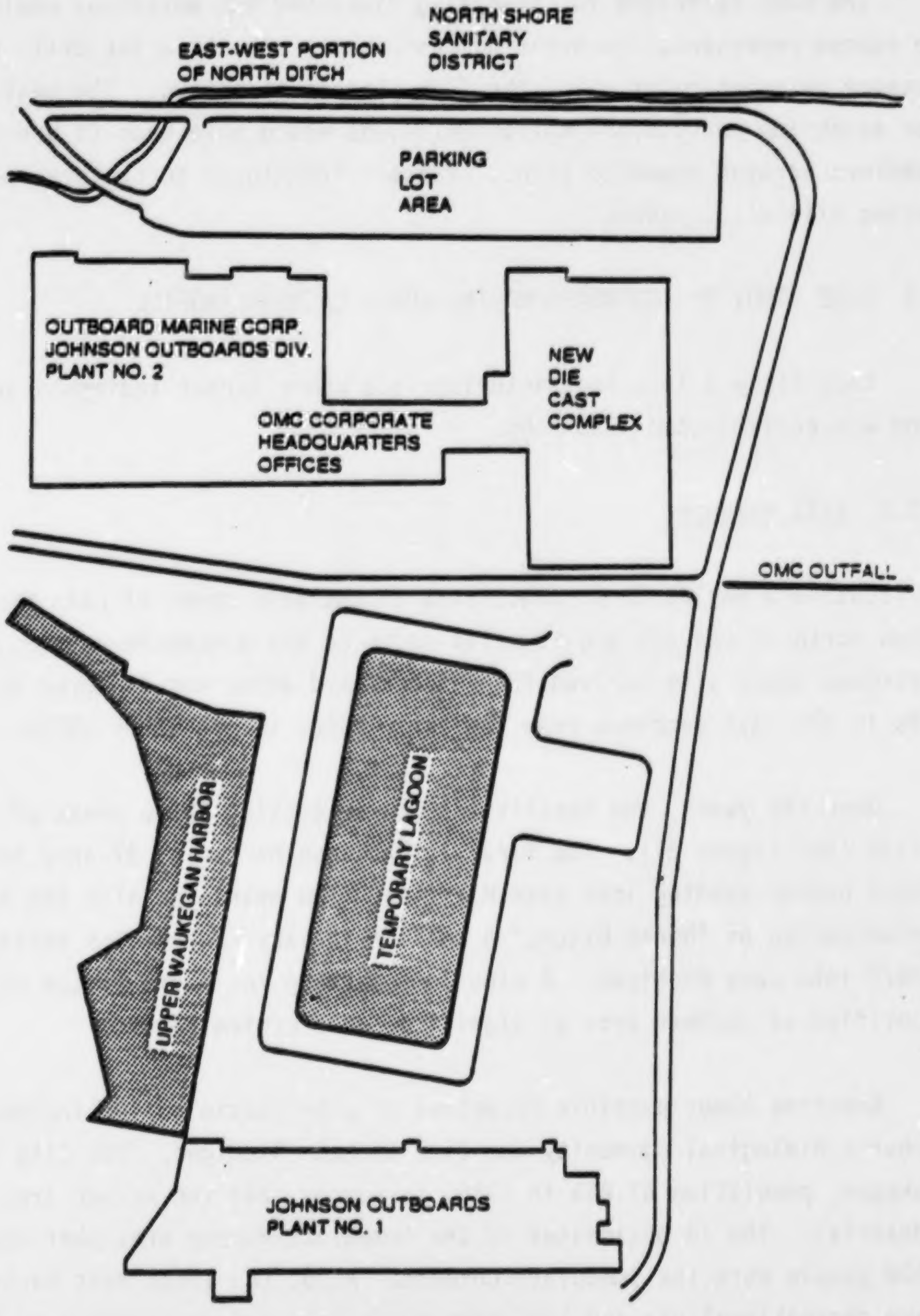

NORTH SHORE
SANITARY
DISTRICT
EAST-WEST PORTION
OF NORTH DITCH
PARKING
LOT
AREA
OUTBOARD MARINE CORP.
JOHNSON OUTBOARDS DIV.
PLANT NO. 2
NEW
DIE
CAST
COMPLEX
OMC CORPORATE
HEADQUARTERS
OFFICES
OMC OUTFALL
UPPER WAUKEGAN HARBOR
TEMPORARY LAGOON
JOHNSON OUTBOARDS
PLANT NO. 1

Figure 27. Map of Case Study 5 site.

OMC purchased roughly 9 million pounds of PCBs from Monsanto Co. over a 20-year period beginning in the early 1950s. OMC used the PCBs as hydraulic fluids in die casting machines and related equipment. This equipment leaked routinely and the fluids ran from the plant floor into floor drains that discharged into Waukegan Harbor and North Ditch. EPA estimated that as much as 20 percent of the PCBs purchased could have been discharged.

It was not until 1975 that the Illinois Environmental Protection Agency (IEPA) discovered the high levels of PCBs in soils and harbor sediments near OMC's plant. This discovery was triggered by a 1971 EPA study that showed PCB concentrations in Lake Michigan fish. In 1976, the EPA began to regulate PCB disposal. At that time, OMC began to sample its outfalls and then sealed two outfalls leading to North Ditch, pursuant to a joint Administrative Enforcement Order by EPA and IEPA (70). OMC later declined to immediately remove sediments contaminated with PCBs, as demanded by EPA. When clean-up negotiations among EPA, IEPA, and OMC failed, legal actions were filed. These legal actions were still pending in early 1988. Superfund money for this site became available in 1983.

5.5.2 Objectives

The objective of the APA for this site was to model the exposure of downwind receptors to PCBs during baseline conditions.

5.5.3 Scoping

Existing data were collected and reviewed to provide a working knowledge of the site history, conditions, and environmental setting. No information was uncovered that indicated a need to modify the air pathway analysis objectives.

5.5.4 Overview of Fieldwork for Site Characterization

Discovery steps through site characterization led to the conclusion that PCB concentrations were significant and that PCB release to the surrounding environment could follow a number of pathways.

Waukegan Harbor--

EPA contractors estimated that in Slip Number 3 in the harbor about 7,200 cubic yards of muck, varying in thickness from 2 to 5 feet, was contaminated by about 167,200 pounds of PCBs. Concentrations typically exceeded 500 ppm. Another 3,700 cubic yards of sand and silt (about 7 feet thick) were contaminated by about 138,000 pounds of PCBs. In one localized area near a former OMC outfall, concentrations exceeded 10,000 ppm.

In the upper harbor about 35,700 cubic yards of muck, 1 to 5 feet thick, were contaminated with approximately 5,000 pounds of PCBs. Concentrations here typically were 50 to 500 ppm.

North Ditch--

Contractors broke the North Ditch into three areas for study. In the "crescent ditch," about 28,900 cubic yards of soil, roughly 25 feet thick, were contaminated by about 403,700 pounds of PCBs, creating concentrations ranging from 5,000 to 38,000 ppm. Another 2,300 cubic yards of soil 3 feet thick north of the die storage area were contaminated by an estimated 200 pounds of PCBs. Concentrations here typically were about 200 ppm.

The "oval lagoon," about 27 feet deep, contained about 14,600 cubic yards of soil contaminated by about 85,500 pounds of PCBs in the top 5 feet. Concentrations within those 5 feet were about 26,000 ppm; no data were available for below 5 feet.

In the main part of North Ditch, about 25,000 cubic yards of soil about 25 feet thick were contaminated by at least 4,300 pounds of PCBs. Concentrations in 200 feet of the ditch's western portion were typically above 5,000 ppm PCBs and another 1,000 feet of the central/western portion of the ditch showed concentrations of 500 to 5,000 ppm.

Parking Lot--

The parking lot also showed significant contamination in contractor studies. Approximately 278,000 pounds of PCBs were found in 105,000 cubic yards of soil. Volatilization was thought to be slight because of soil cover and partial pavement. Air emission estimates were not made.

5.5.5 Undisturbed Emissions Survey

No air monitoring for the presence of PCBs was conducted at the site. Dispersion modeling was used to estimate rates of PCB volatilization. The PCB concentration expected in solution at the sediment/water interface was estimated by mixing contaminated sediment with water, decanting the mixture, and measuring the PCB concentration in the water. This concentration number was plugged into transport rate equations. Contractors assumed a volatilization rate of 3.8 mg/m^2/hour from a saturated solution, based on data provided by General Electric Corporation. Assuming volatilization to be proportional to the PCB concentration in the solution, calculations showed that roughly 3.3 pounds of PCB were leaving the harbor portion of the OMC site through the atmosphere per month. The rate would vary positively with temperature. EPA estimated that 12 to 40 pounds of PCBs were volatilizing from the harbor each year. In addition, the North Ditch was estimated to be contributing another 15 pounds of PCBs to the atmosphere per year.

5.5.6 Disturbed Emissions Survey

No field measurements or modeling estimates were made to assess the emissions during site disturbances. It would be advisable to conduct a laboratory or field study to determine the degree to which volatilization will increase during dredging or other site remediation work. The emission estimates could then be used as inputs to dispersion models to assess the impact on downwind receptors.

5.5.7 Development of BEEs

As discussed above, undisturbed (baseline) emission estimates were developed for two of the three operable units at the site. These estimates were 12 to 40 lb. PCB/year and 15 lb. PCB/year. No disturbed emission estimates were developed. If emission rate data were available for waste in the disturbed state (e.g., flux chamber test data), then disturbed emission estimates should have been developed using the same modeling approach used to develop the BEEs.

5.5.8 Summary

The air pathway for contaminant transport was assessed at this site for undisturbed conditions using modeling techniques. This was a valid, cost-effective option, given the logistical problems of making direct field measurements at this site and the low probability of detecting PCBs in the ambient air downwind of the site.

The best technique for assessing the disturbed PCB emissions would have been to dredge up representative contaminated material and directly measure emissions with a flux chamber. As an alternative, this approach could be modified to perform the work in a laboratory setting.

SECTION 6

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APPENDIX A

ANNOTATED BILIOGRAPHY

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Baker and Mackay evaluate performance of four air dispersion models to calculate the ambient air concentration of vinyl chloride versus measured concentration downwind of a landfill. The vinyl chloride emission rate was calculated using Shen's modification of Farmer's gas migration equation. The air dispersion models used are a ground level point source model, two virtual point source mdoels, and a simple box model.

VIII. Balfour, W.D., R.G. Wetherold, and D.L. Lewis. Evaluation of Air Emissions from Hazardous Waste Treatment, Storage, and Disposal Facilities. EPA 600/2-85/057, U.S. Environmental Protection Agency. Cincinnati, OH, 1984. 2 vol.

Emission rates based on direct and indirect emission measurements were compared to emission rates calculated from predictive models. Emission rate measurement techniques were also compared against each other. Emission measurement techniques include surface isolation flux chamber, vent sampling, concentration profile, transect, and mass balance. Predictive models include the Thibodeaux, Parker, and Heck Models (non-aerated surface impound), the Thibodeaux-Hwang Model (land treatment), and an API model (tanks). Details for each measurement technique and model are provided.

IX. **Balfour, W.D., C.E. Schmidt, and B.M. Eklund. Sampling Approaches for the Measurement of Volatile Compounds at Hazardous Waste Sites. Radian Corporation, Austin, TX, no date. 29 pp.**

Sampling techniques for measuring volatile emission rates and for measuring soil gas concentrations are discussed. Emission rate techniques included are emission isolation flux chamber, vent sampling, concentration profile, transect, and mass balance. Soil gas concentration techniques are headspace analysis of soil cores, soil gas probes (ground probe), and passive samplers.

Each approach is described, and the applicable equations are presented.

X. **Balfour, W.D., and C.E. Schmidt. Sampling Approaches for Measuring Emission Rates from Hazardous Waste Disposal Facilities. Radian Corporation, Austin, TX, 1984. 13 pp.**

Balfour and Schmidt present five sampling approaches for measuring volatile emissions: surface emission isolation flux chamber, vent sampling, concentration-profile, transect technique, and mass balance. A comparison of the applicability of each technique to various TSDF sites or units is given.

XI. **Balfour, W.D., B.M. Eklund, and S.J. Williamson. Measurement of Volatile Organic Emissions from Subsurface Contaminants. Radian Corporation, Austin, TX, 1985. 20 pp.**

This paper presents results of field measurement performed with the surface emission isolation flux chamber. It also evaluates the effect of six operating variables on measured emission rate and appropriateness of statistical sampling procedure for area sources, and provides an analysis of variability in the method.

XII. **Banerjee, P., and D.H. Homer. The Impacts of Using Assumed Versus Site-Specific Values in Determining Fate and Transport. In: Superfund'87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 126-128.**

This article does not discuss emission rate measurement; rather, it emphasizes the importance of the need to obtain site-specific data rather then assumed or literature-derived values as inputs to risk assessment.

XIII. **Berrafato, L.R., and R.A. Wadden. Predicted vs. Measured Air Emissions of Volatile Organics from a Simulated Hazardous Waste Lagoon. In: Toxic Hazardous Wastes, Proceedings of the 18th Mid-Atlantic Hazardous Waste Conference, Chem. Ind. Inst. Toxicol., Research Triangle Park, NC, 1986. pp. 515-525.**

Evaporation of toluene and chlorobenzene from a simulated lagoon was measured based on the liquid concentration of these chemicals in the lagoon. The evaporation rate was compared to a predictive model similar to the Mackay-Leinonen Model. The results showed the model may be useful for order of magnitude estimates.

XIV. Bilsky, I.L. Air Pollution Aspects of Hazardous Waste Disposal in Texas. Environmental Progress, 5(2):123-129, 1986.

This article examines the Texas administrative review process for proposed hazardous waste disposal facilities. A case study of a waste disposal facility application is reviewed.

XV. Blasko, M.J., B.F. Cockroft, W.C. Smith, and P.F. O'Hara. Design of Remedial Measures and Waste Removal Program, Lackawanna Refuse Superfund Site. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 367-370.

This article discusses the development of the design and construction bid package for the remedial measures and removal program. No information on emissions data is given. The RI report would have to be reviewed directly to see if a case study exists.

XVI. Breton, M., T. Nunno, P. Spawn, W. Farino, and R. McInnes. Evaluation and Selection of Models for Estimating Air Emissions from Hazardous Waste Treatment, Storage, and Disposal Facilities. EPA-450/8-34-020, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Emission Standards and Engineering Division, Research Triangle Park, NC, 1984. 157 pp.

Mathematical models describing the release rate of volatile air emissions from hazardous waste treatment, storage, and disposal facilities were compiled and reviewed. Mathematical modeling techniques which predict volatile air emission release rates from landfills, landfarms, surface impoundments, storage tanks. wastewater treatment processes, and drum handling and storage facilities were assessed. Existing field test validation efforts were also reviewed. Models reviewed include: landfill -- Farmer Model, Shen modification of Farmer Model, Thibodeaux a Model, Thibodeaux Convective "Add On" Model, Thibodeaux b Model, and Shen's Open Dump Model; land treatment -- Thibodeaux-Hwang Model and Hartley Model; lagoons -- Mackay and Leinonen Model, Mackay and Wolkoff Model, Thibodeaux, Parker and Heck model, Shen Model, Smith Model, and McCord Model.

XVII. Caputo, Jr., K., and R.L. Bittle. Case History: A Superfund Cleanup in Central Pennsylvania. In: Hazardous and Toxic Wastes: Technology, Management and Health Effects, S.K. Majumdar and E.W. Miller, eds. Pennsylvania Academy of Science, Easton, PA, 1984. pp. 228-241.

This chapter is not relevant to the current project; no emission measurements are reported. Caputo and Bittle describe the general details of an emergency cleanup at an industrial site.

XVIII. Caravanos, J., and T.T. Shen. The Effect of Wind Speed on the Emission Rates of Volatile Chemicals from Open Hazardous Waste Dump Sites. Source unknown.

This article presents a modified diffusion equation (Shen Model), which includes wind speed as a variable. Experimental data are presented for benzene, carbon tetrachloride, and trichloroethylene applied to soil, which approximate a spill. The equation also could be applied to waste exposed at surface.

XIX. Cassis, J.A., E.P. Kunce, and T.A. Pederson. Remedial Action at Uncontrolled Hazardous Waste Sites: Problems and Solutions. In: Hazardous Waste Management for the 1980s, T.L. Sweeney, H.G. Bhatt, R.M. Sykes, and O.J. Sproul, eds. Ann Arbor Science, Ann Arbor, MI, 1982. pp.241-264.

This chapter is not relevant to this program. The authors describe a remedial action plan for the Pollution Abatement Services Oswego Site in Oswego, New York.

XX. Cimorelli, A.J. Palmerton Zinc National Priorities List Site: Atmospheric Deposition Analysis of Cadmium, Zinc, Lead and Copper in the Vicinity of the New Jersey Zinc Palmerton Facility. U.S. Environmental Protection Agency Region III Air Management Division, 1986. 93 pp.

Cimorelli discusses heavy metal deposition from stack emissions. Meteorological data are used to identify areas of high deposition, to design a soil sampling program.

XXI. Countess, R.J., R. Brewer, and R.J. Gordon. Sampling Airborne Toxic Organics by Remote Control. Presented at the 78th Annual Meeting of the Air Pollution Control Association, Detroit, MI, 1985. 16 pp.

This paper describes a radio-controlled air sampler, which would be useful as a sampling method.

XXII. Cowherd, C. Measurement of Particulate Emissions from Hazardous Waste Disposal Sites. For presentation at: 78th Annual Meeting, Air Pollution Control Association, Detroit, MI, June 16-21, 1985.

Article describes the MRI wind tunnel and exposure profiling techniques for particulate emissions rate measurement. The MRI wind tunnel is a portable wind tunnel which can be used for direct emissions measurement. The exposure profiling technique is used for indirect emissions measurement and is similar to the transect technique.

XXIII. Cox, R.D., K.J. Baughman, and R.F. Earp. A Generalized Screening and Analysis Procedure for Organic Emissions from Hazardous Waste Disposal Sites. In: Proceedings of the 3rd National Conference and Exhibition on Management of Uncontrolled Waste Sites, Washington, D.C., 1982.

The authors describe a technique developed by Radian Corporation for analysis of gas, liquid, and solid environmental samples. The technique uses gas chromatography with flame ionization, photoionization and Hall electrolytic conductivity detectors, as well as mass spectrometry.

XXIV. DeWolf, G.B., and R.G. Wetherold. Protocols for Calculating VOC Emissions from Surface Impoundments Using Emission Models: Technical Note. Radian Corporation, Austin, TX, EPA Contract No. 68-02-3850, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1984. 34 pp.

DeWolf and Wetherold present the Thibodeaux models for aerated and nonaerated steady-state impounds and the Mackay and Leinonen Model for unsteady-state impounds. Input variables are defined, sources of these variables are suggested, and approximate precision levels for the variables are given. Physical property inputs are discussed and methods for their estimation are given, along with selected values for some materials.

XXV. DeWolf, G.B., and R.G. Wetherold. Protocols for Calculating VOC Emissions from Land Applications Using Emission Models. Radian Corporation, Austin, TX, EPA Contract No. 68-02-3850, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1984. 28 pp.

The authors present the Thibodeaux-Hwang Model for land treatment and the Farmer Model for landfills. Input variables are defined, sources of the variables are suggested, and approximate precision levels for the variables are given. Physical property inputs are discussed and methods for their estimation are given, along with selected values for some materials.

XXVI. Dupont, R.R. A Flux Chamber/Solid Sorbent Monitoring System for Use in Hazardous Organic Emission Measurements from Land Treatment Facilities. Presented at the 79th Annual Meeting of the Air Pollution Control Association, Minneapolis, MN, 1986. 15 pp.

This paper reports on testing of the emission isolation flux chamber with Tenax\ tubes as the sampling media.

XXVII. Dupont, R.R. A Flux Chamber/Sorbent Tube Monitoring System for Hazardous Organic Emission Measurements from Land Treatment Facilities. In: 192nd National Meeting, American Chemical Society, Division of Environmental Chemistry, 26(2):394-397, 1986.

This is not useful for a case study; the technology is already known. The article reports that testing of the emission isolation flux chamber with Tenax\ tubes for sample collection was effective for measuring specific volatile species under both laboratory and field conditions.

XXVIII. Dupont, R.R. Measurement of Volatile Hazardous Organic Emissions. Journal of the Air Pollution Control Association, 37(3):168-176, 1987.

An emissions isolation flux chamber was laboratory tested in combination with Tenax\ and charcoal tube sampling to determine the recovery efficiencies for selected organics. The testing validates the use of a "Radian-style" flux chamber. Testing included the use of flow rates significantly below the standard protocol.

XXIX. Eklund, B.M., W.D. Balfour, and C.E. Schmidt. Measurement of Fugitive Volatile Organic Emission Rates. Environmental Progress, 4(3):199202, 1985.

This article describes the design and operation of a "Radian-style" emission isolation flux chamber. It also provides limited data from several projects, which can be used as emission measurement case studies.

XXX. Eklund, B. Detection of Hydrocarbons in Groundwater by Analysis of Shallow Soil Gas/Vapor. Radian Corporation, Austin, TX, 1985. 78 pp.

This report describes five methods of measuring soil vapor concentrations: surface flux chamber, soil probe, downhole flux chamber, accumulator, and soil coring. All five methods would be useful for data collection for direct measurement and/or predictive modeling.

XXXI. Eklund, B.M., W.D. Balfour, and C.E. Schmidt. Measurement of Fugitive Volatile Organic Compound Emission Rates with an Emission Isolation Flux Chamber. For presentation at: AIChE Summer National Meeting, Philadelphia, PA, 1984. 8 pp.

The authors present the procedures for using the surface emission isolation flux chamber for direct emission rate measurement. Also presented are the results of measurements at two spill sites, three landfills, several surface impounds, a landfarm, and a remedial action.

XXXII. Eklund, B.M., M.R. Kienbusch, D. Ranum, and T. Harrison. Development of a Sampling Method for Measuring VOC Emissions from Surface Impoundments. Radian Corporation, Austin, TX, no date. 7 pp.

This paper describes the development program for evaluating and modifying the design and operation of the surface isolation flux chamber for use on surface impounds.

XXXIII. Enfield, C.G., R.F. Carsel, S.Z. Cohen, T. Phan, and D.M. Walters. Approximating Pollutant Transport to Ground Water. Ground Water, 20(6): 711-722, 1982.

This article does not provide information on emission rate determination. It present three transport models for evaluating the movement of organic chemicals through the soil to the groundwater. The models include losses due to degradation and sorption. Field data are compared to the models.

XXXIV. Engineering Science, Inc. Determination of Air Toxic Emissions from Non-Traditional Sources in the Puget Sound Region. EPA 910/9-86-148, U.S. Environmental Protection Agency, Region X and Puget Sound Air Pollution Control Agency, Seattle, WA, 1986. 108 pp.

This report develops emission estimates for several selected sources in the Puget Sound Region including POTWs, industrial wastewater treatment plants, Superfund sites, municipal landfills, and TSDFs. Emissions are based on theoretical equations. The report contains some useful examples of theoretical equation applications. The report may also provide case study site information.

XXXV. Farino, W., P. Spawn, M. Jasinski, and B. Murphy. Review of Landfill AERR Models. In: Evaluation and Selection of Models for Estimating Air Emissions from Hazardous Waste Treatment, Storage, and Disposal Facilities. Revised Draft Final Report. Contract No. 68-02-3168, U.S. Environmental Agency, Office of Solid Waste, Land Disposal Branch, 1983. pp. 5-1 - 5-13.

This section describes six predictive models that estimate volatile emissions: Farmer, Shen's modification of Farmer, Thibodeaux (three variations), and Shen's Open Dump. The first five models are based primarily on gas diffusion through the landfill cover.

XXXVI. Farmer, W.J., M.S. Yang, J. Letey, W.F. Spencer, and M.H. Roulier. Land Disposal of Hexachlorobenzene Wastes: Controlling Vapor Movement in Soils. In: Land Disposal of Hazardous Wastes. Proceedings of the Fourth Annual Research Symposium, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, San Antonio, TX, March 6, 7, and 8, 1978. pp. 182-190.

Farmer presents a predictive equation for determining hexachlorobenzene vapor diffusion through a soil cover. Volatilization through soil, water, and polyethylene film was studied in laboratory simulations. The predictive equation should be applicable to other waste types.

XXXVII. Farmer, W.J., M.S. Yang, J. Letey, and W.F. Spencer. Land Disposal of Hexachlorobenzene Wastes: Controlling Vapor Movement in Soil. EPA-600/280-119, U.S. Environmental Protection Agency, Office of Research and Development, Municipal Environmental Research Laboratory, Cincinnati, OH, 1980. 69 pp.

The volatilization fluxes of hexachlorobenzene through a covering of soil, water, and polyethylene film were simulated in the laboratory. Volatilization through soil was directly related to soil porosity. Farmer develops a diffusion equation for determining flux rates through the soil covering.

XXXVIII. Gillespie, D.P., F.J. Schauf, and J.J. Walsh. Remedial Actions at Uncontrolled Hazardous Waste Sites, Survey and Case Study Investigation. In: Proceedings of the Second National Symposium on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Worthington, OH, 1982. pp. 369-374.

This paper is not useful. It discusses how nearly half of all remedial actions completed by 1980 were ineffective at cleaning up the sites.

XXXIX. Gravitz, N. Derivation and Implementation of Air Criteria During Hazardous Waste Site Cleanups. Journal of the Air Pollution Control Association, 35(7):753-758, 1985.

This article presents an approach for developing fenceline air monitoring criteria to protect community health. The approach is dependent on developing acceptable community exposure levels, and back calculating the fenceline concentration by assuming Gaussian wind dispersion. The method does not require emissions measurement.

XL. Greenberg, M. A Review of: 1) A Technical Approach for Sampling and Analysis of VOCs at Hazardous Waste Sites and 2) Some Case Studies in New Hampshire. Presented before the Fall Meeting, Air Pollution Control Association New England Section, Conference on Air Toxics, Worcester, MA, October 6-7, 1986. 30 pp.

This document contains overhead slides for a conference presentation on sampling VOCs in ambient air at landfills. Case studies are not worked up as emission estimates.

XLI. Hanisch, R.C., and M.A. McDevitt. Protocols for Sampling and Analysis of Surface Impoundments and Land Treatment/Disposal Sites for VOCs. EPA Contract No. 68-02-3850, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1984. 88 pp.

The report gives detailed description for analysis of volatile organics by Radian gas chromatography with multiple detectors (GC/MD) system and gas chromatography with mass spectrometry (GS/MS) system. The report gives a brief discussion of predictive emission models and lists inputs to models, but does not present models. A description of a statistical approach to collecting sufficient samples for representativeness is included.

XLII. Helsing, L.D., M.P. Morningstar, J.B. Berkowitz, and T.T. Shen. Risk Analysis of Pollutants at Hazardous Waste Sites: Integration Across Media is the Key. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 471-475.

This paper describes the types of pollutants frequently found at hazardous waste sites and how they can be transferred from one media to another. This paper describes how all media need to be taken into account when performing risk analysis. No information on emission rate determination is provided.

XLIII. Hwang, S.T. Measuring Rates of Volatile Emissions from Non-Point Source Hazardous Waste Facilities. Presented at the 75th Annual Meeting of the Air Pollution Control Association, New Orleans, LA, 1982. 22 pp.

This paper presents Concentration Profile, Plume Mapping (transect), and Upwind/Downwind models for indirectly measuring emission rates.

XLIV. Hwang, S.T. Toxic Emissions from Land Disposal Facilities. Environmental Progress, 1(1):46-52, 1982.

Hwang gives theoretical equations for emission rate estimates from surface impoundments (natural surface and aerated), landfills (based on soil diffusion), and land treatment (oily wastes). The equations require knowledge of waste and site characteristics to determine variables and coefficients. All equations would be difficult to apply for a complex waste, requiring computer calculation. The equations can be applied more easily to a single component waste, or its primary components.

XLV. Hwang, S.T. Comparison of Model Predicted Volatile Emission Rates Versus Results of Field Measurements at Hazardous Waste Sites. Presented at: American Institute of Chemical Engineers, National Meeting, Summer 1984. American Institute of Chemical Engineers, New York, NY. 18 pp.

Paper presents a comparison of measured and estimated emission rates based on field sampling results and theoretical models. Measurements were performed at landfills, surface impounds, and land treatment facilities. Field sampling techniques used were concentration profile, transect, and surface emission isolation flux chamber. The predicted emission rates were generally within the confidence intervals of the measured emission rates, although the author indicates that more study is required to validate the models. The specific models used are referenced but not discussed.

XLVI. Hwang, S.T. Estimating and Field-Validating Hazardous Air Emissions from Land Disposal Facilities. In: Third Pacific Chemical Engineering Conference, Seoul, Korea, 1983. pp. 338-343.

Models for estimating volatile emissions are reviewed, including Shen's modification of Farmer's equation (landfill), the Thibodeaux-Hwang equation (land treatment) and surface impound equation. Predicted versus measured emissions (concentration profile and upwind/downwind techniques) are compared, but limited data are given.

XLVII. Hwang, S.T. Model Prediction of Volatile Emissions. Environmental Progress 4(2):141-144, 1985.

Hwang presents a comparison of measured and predicted emission rates. Measurement techniques include transect and concentration profile techniques. Isolation flux chambers and upwind/downwind are also discussed. The article contains limited data from potential case studies.

XLVIII. ICF, Incorporated. The RCRA Risk-Cost Analysis Model Phase III Report Appendices. Submitted to the Office of Solid Waste, Economic Analysis Branch, U.S. Environmental Protection Agency, 1982. Appendix E, 31 pp.

Appendix E describes natural chemical, physical, and biological processes that reduce the concentration of chemicals in the environment. These processes are the basis for deriving surface and groundwater decay rates for the chemicals included in the RCRA Risk-Cost Analysis Model. Important for baseline emission rate estimates is the discussion on volatilization from water.

XLIX. Jubach, R.W., R.R. Stoner, T.F. Iaccarino, and D.R. Smiley. An Atmospheric Field Program Conducted at a Hazardous Waste Site. Presented at the 78th Annual Meeting of the Air Pollution Control Association, Detroit, MI, 1985. 14 pp.

This study characterizes the atmospheric dispersion at a hazardous waste site from ground level release. The study consists of releasing a tracer gas and measuring the concentration with two sampling arrays (i.e., transect techniques). Measuring the of actual waste releases are not included. Downwind data could be useful as a theoretical case study.

L. Kaplin, E.J., A.J. Kurtz, and M. Rahimi. VOC Sampling for Emission Rate Determination and Ambient Air Quality on an Inactive Landfill. Presented at New England Section, Air Pollution Control Association, Fall 1986 Conference, Worcester, MA, October 6-7, 1986. 27 pp.

This paper describes sampling performed at an inactive landfill in New York (a municipal waste landfill containing industrial waste). Sampling included ambient air, emission flux chamber (crude), crevices, and vent, sampled with Tenax, PUF/GFF, mylar bags, impingers, and high volume samplers with GFF. Flux measurements included both covered and uncovered areas. Data are somewhat limited, but this study may be useful as a case study.

LI. Karably, L.S., and K.B. Babcock. Effects of Environmental Variables on Soil Gas Surveys. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 97-100.

This may be useful as a case study if sufficient soil data are available. Soil gas was measured at 40 locations and over time at a fire fighting training area. This paper reports how environmental conditions (principally weather) affected results. Limited analytical data are presented.

LII. Karimi, A.A., W.J. Farmer, and M.M. Cliath. Vapor-phase Diffusion of Benzene in Soil. Journal of Environmental Quality, 16(1):38-43, 1987.

The authors use Farmer's diffusion model and laboratory testing method to determine benzene emission rates through soil (i.e., landfill emissions). The effects of soil bulk density and moisture content are investigated.

LIII. Keinbusch, M.R. Measurement of Gaseous Emission Rates from Land Surfaces using an Emission Flux Chamber: Users Guide, EPA Contract 68-02-3889, Radian Corporation, Austin, TX, 1986.

This document includes a detailed description for using the emission isolation flux chamber, including design of sampling program, QA/QC, data reduction, and examples.

LIV. Kerfoot, H.B. Soil-Gas Measurement for Detection of Groundwater Contamination by Volatile Organic Compounds. Environmental Science and Technology, 21(10):1022-1024, 1987.

This article describes sampling using a ground probe system for soil gas. Soil gas data are correlated with groundwater data showing good correlation. Soil gas data are correlated with soil probe depth below ground surface, also showing good correlation. Ground water was at shallow depth in this study (3-4m). Data could be used as a case study if additional soil characteristics data are available.

LV. Kerfoot, H.B., and P.B. Durgin. Soil-Gas Surveying for Subsurface Organic Contamination: Active and Passive Techniques. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 523-524.

This article provides an overview of considerations in designing a soil-gas survey. It does not provide information on sampling techniques for air pathway assessment.

LVI. Lepic, K.A., and A.R. Foster. Remediation at a Major Superfund Site: Western Processing -- Kent, Washington. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 78-84.

This article summarizes a remedial investigation conducted at a Western Processing site. Continuous upwind and downwind air monitoring was conducted, as well as some location-specific sampling. It may be useful as a case study. No data on air monitoring are presented; the author would have to be contacted.

LVII. Lewis, R.G., B.E. Martin, D.L. Sgontz, and J.E. Howes. Measurement of Fugitive Atmospheric Emissions of Polychlorinated Biphenyls from Hazardous Waste Landfills. Environmental Science and Technology, 19(10):986-991, 1985.

This article describes air sampling for PCBs at three uncontrolled landfills and one controlled landfill. Emission rates were not calculated. The data set may be usable for calculating emission rates. Sampling was performed using low-volume and high-volume samplers and PUF cartridges.

LVIII. Mackay, D.M., P.V. Roberts, and J.A. Cherry. Transport of Organic Contaminants in Groundwater. Environmental Science and Technology, 19(5): 384-392, 1986.

This article describes the mechanisms involved in the transport of organic chemical contaminants in ground water, including advection, dispersion, sorption and transformation.

LIX. Mackay, D., and P.J. Leinonen. Rate of Evaporation of Low-Solubility Contaminants from Water Bodies to Atmosphere. Environmental Science and Technology, 9(13): 1178-1180, 1975.

The authors present predict models (Mackay and Leinonen) for emission rates from aqueous systems. Equations are presented for both steady and unsteady state systems.

LX. Mackay, D., and A.T.K. Yeun. Mass Transfer Coefficient Correlations for Volatilization of Organic Solutes from Water. Environmental Science and Technology, 17(4):211-217, 1983.

Volatilization rates of organic compounds in water were measured in a wind-wave tank for compounds of varying Henry's Law Constants. The data yielded correlations for liquid and vapro-phase transfer coefficients as a function of windspeed, and showed that interactions did not occur when mixtures of compounds volatilized simultaneously.

LXI. Marquardt, G.D. Toxic Air Quality Investigation at a Hazardous Waste Site. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 284-295.

This article does not provide data for baseline conditions. However, it may be useful as a case study. Sampling was performed upwind, on site, and downwind during field investigation (drilling) and during a controlled release from a gas well. Sampling techniques could be used for indirect measurement of baseline emissions; techniques include Tenax\, carbon molecular sieve, high-volume particulate sampler, and PUF.

LXII. Meegoda, N.J., and P. Ratnaweera. A New Method to Characterize Contaminated Soils. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 385-389.

This paper is not related to emission rate determination; it presents an electrical method to determine engineering characteristics of soil.

LXIII. Miller, G.C., V.R. Herbert, and R.G. Zepp. Chemistry and Photochemistry of Low-Volatility Organic Chemicals on Environmental Surfaces. Environmental Science and Technology, 21(12):1164-1167, 1987.

This article discusses factors affecting the transformation, mobility, and fate of xenobiotic chemicals (specifically dioxins and PAHs). Emphasis is placed on discussing effects on and near the soil surface and factors that affect the rate of photolysis.

LXIV. Panaro, J.M. Air Monitoring and Data Interpretation During Remedial Action at a Hazardous Waste Site. In: Hazardous Wastes and Environmental Emergencies: Management, Prevention, Cleanup, Control, Hazardous Materials Control Research Institute, Houston, TX, 1984. pp.160-164.

Panaro describes the air monitoring program employed during initial remedial measures at a chemical recycling plant. He does not address emission estimates.

LXV. Polcyn, A.J., and H.E. Hesketh. A Review of Current Sampling and Analytical Methods for Assessing Toxic and Hazardous Organic Emissions from Stationary Sources. Journal of the Air Pollution Control Association, 35(1):54-60, 1985.

This article is a brief review of sampling methods (i.e., sample collection media) and analytical methods. The methods are summarized in tables, and give references for detailed descriptions. The article does not discuss measurement techniques (i.e., sampling design) or modeling.

LXVI. Quimby, J.M., R.W. Cibulskis, and M. Gruenfeld. Evaluation and Use of a Portable Gas Chromatograph for Monitoring Hazardous Waste Sites. Source unknown.

This paper evaluates the use of the Century Systems Organic Vapor Analyzer Model OVA-128 which is a portable gas chromatograph with a fume ionization detector (GC-FID). The paper addresses instrument operating performance, QA/QC consideration, operational difficulties and recommended field uses. Instruments can be used to perform field screening of ambient air, as well as other uses.

LXVII. Radian Corporation. Review of Soil Gas Sampling Techniques. Austin, TX, 1983. 26 pp.

Report presents the results of a literature review to identify techniques applicable to soil gas sampling and measurement.

LXVIII. Radian Corporation. 3M Foam Evaluation for Vapor Mitigation: Technical Memorandum. Sacramento, CA, 1986. 95 pp.

The effectiveness of temporary and stabilized foam for controlling VOC emissions from petroleum refinery waste was tested. Testing was performed using the surface emission isolation flux chamber.

LXIX. Radian Corporation. Air Quality Engineering Manual for Hazardous Waste Site Mitigation Activities, Revision No. 2. Sacramento, CA, 1987. 291 pp.

This guidance document provides general information for designing and reviewing air monitoring programs for hazardous waste site remedial programs. An overview of New Jersey's agency involvement in the remedial process is given. Sampling and analysis methods are discussed in detail.

LXX. Radian Corporation. Ambient Air Monitoring at Hazardous Waste and Superfund Sites, Revision No. 2. Sacramento, CA, 1987. 389 pp.

This guidance document provides information for reviewing air quality engineering activities for hazardous waste site remediation programs. It also provides an overview of the phases of the hazardous site remediation process and the role of New Jersey's agencies in the process. Descriptions are given for types of waste sites, potential air contaminants, and basic remedial processes.

LXXI. Radian Corporation. Survey and Assessment of Air Emission Modeling Techniques for Landfills. Draft Final Report. EPA Contract 68-01-7287, U.S. Environmental Protection Agency, Washington, D.C., 1988. 115 pp.

Article reviews theoretical models for landfill air emissions including: Farmer Model, Shen Model, Thibodeaux a Model, Thibodeaux Logrithmic Gradient Model, RTI Closed Landfill Model, Thibodeaux Convective "Add On" Model, Thibodeaux b Model, Thibodeaux Exact Model, Arnold's Open Landfill Model, Shen's Open Landfill Model, and RTI Open Landfill Model.

LXXII. Saeger, M.L., and E.E. Rickman, Jr. Final Report: Ambient Air Monitoring at Hazardous Waste Treatment, Storage, and Disposal Facilities, Phase I. EPA Project Number 68-02-4326, U.S. Environmental Protection Agency, Emissions Standards and Engineering Division, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1968.

The authors contacted several state and federal regulatory agencies and treatment, storage and disposal facilities (TSDFs) to determine the air monitoring requirements for TSDFs. Few of the states contacted had established requirements, and there was no consistency among states. The program was of a limited scope and was intended to determine if a study should be conducted to assess the feasibility of conducting air monitoring programs at TSDFs.

LXXIII. Schmidt, C.E., and D.L. Gordy. Designing Air Monitoring Programs for Remediation at Hazardous Waste Sites. Presented at the Annual Conference of the Air Pollution Control Association, San Francisco, CA, 1985. 14 pp.

This paper presents a methodology for developing site-specific air monitoring programs for hazardous waste site remediation. The information presented focuses on fugitive gas phase air contaminants.

LXXIV. Schmidt, C.E., and J.K. Meyer-Schmidt. Assessment, Monitoring, and Modeling From a Superfund Site Remedial Action. Presented at the Air Pollution Control Association Annual Conference, San Francisco, CA, 1985. 20 pp.

This paper gives a brief overview of RI/FS activities performed at the McColl waste site in Fullerton, California. Measurements included surfaces screening survey, surface flux, ground probes, and downhole flux. Indirect measurements were performed by ambient air sampling. Modeling was used to predict downwind concentrations from direct measurement. Data can be used directly as a case study for both direct and indirect emission estimates. Data can also be used with predictive models.

LXXV. Schmidt, C.E., R. Stephens, and G.A. Turl. Case Study: Control and Monitoring of Air Contaminants During Site Mitigation. Radian Corporation, Sacramento, CA, 1987. 8 pp.

This article presents an RI/FS/RM case study where an air pathways assessment was performed at a hazardous waste site. Both baseline and disturbed site air emissions were measured and reported.

LXXVI. Schmidt, C.E., and M.W. Eltgroth. Off-Site Assessment of Air Emissions from Hazardous Waste Disposal Facilities. Reprinted from: Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Spring, MD, 1983.14 pp.

Field data and modeling (Lugrangian model) were used to estimate downwind air concentrations of contaminants using measured disturbed site emissions data. Modeled data were compared to measured data.

LXXVII. Schmidt, C.E., and W.D. Balfour. Direct Gas Emission Measurement Techniques and the Utilization of Emissions Data from Hazardous Waste Sites. Reprinted from: National Conference on Environmental Engineering Proceedings, Environmental Engineering Division, ASCE, 1983. 8 pp.

This article describes direct emissions measurement techniques and discusses various applications of these techniques to waste management. Techniques included are surface and downhole isolation flux chambers, ground probes, and soil vapor monitoring wells.

LXXVIII. Schmidt, C.E., R. Vandervort, and W.D. Balfour. Technical Approach and Sampling Techniques Used to Detect and Map Subsurface Hydrocarbon Contamination. For presentation at the 79th Annual Meeting, Air Pollution Control Association, Minneapolis, MN, 1986. 31 pp.

This paper presents a case study where several direct air emissions measurement techniques were used to detect emissions from a gasoline plume on groundwater about 90 feet below the land surface.

LXXIX. Shen, T.T., and T. J. Tofflemire. Air Pollution Aspects of Land Disposal of Toxic Waste. In: National Conference on Hazardous Material Risk Assessment, Disposal and Management, Miami Beach, FL, April 25-27, 1979. pp. 153-159.

This paper provides a general discussion of the air pollution dangers inherent in landfilling industrial waste, especially co-disposal with municipal waste. Volatilization processes are discussed. Also discussed are methods for reducing the rate of volatile loss.

LXXX. Shen, T.T. Estimating Hazardous Air Emissions from Disposal Sites. Pollution Engineering, 13(8):31-34, 1981.

This article presents Shen's modification of Farmer's equation for the diffusion of volatiles from a landfill, and Ziegler's modification of Arnold's equation for open dumps (also referred to as Shen's open dump equation). A table of diffusion coefficients for selected compounds is given. Two example calculations for PCB emission are also given.

LXXXI. Shen, T.T., and G.H. Sewell. Air Pollution Problems of Uncontrolled Hazardous Waste Sites. Civil Engineering for Practicing and Design Engineers, 3(3):241-252, 1984.

Shen and Sewell provide three theoretical equations for predicting emission rates (Shen landfill model, Shen landfarm model, Shen lagoon model) for volatiles and one for dust. The equations require some field data about soil, waste characteristics, site size, etc., but no direct or indirect measurement of emissions. The equations should be used with caution, and some speciesspecific coefficients may be difficult to determine or infer.

LXXXII. Shen, T.T. Air Pollution Assessment of Toxic Emissions from Hazardous Waste Lagoons and Landfills. Environment International, 11(1):71-76, 1985.

Shen briefly discusses the available methods for determining emission rates and their drawbacks. He does not provide technical detail for the use of methods, but includes isolation flux chamber, transect, concentration profile, and predictive models.

LXXXIII. Shen, T.T. Air Quality Assessment for Land Disposal of Industrial Wastes. Environmental Management, 6(4):297-305, 1982.

Shen presents a models for predicting emission rates from landfills (Shen modification of Farmer), dumps (Arnold Model) and lagoons based on the diffusion theory. Shen also presents data on the comparison of predicted versus measured ambient concentration of PCBs at a New York landfill. This article may be useful as a case study.

LXXXIV. Shen, T.T. Hazardous Air Emissions from Industrial Waste Treatment Facilities. In: Industrial Waste: Proceedings of the Fourteenth Mid-Atlantic Conference, June 27-29, 1982, J.E. Alleman and J.T. Kavanagh, eds., Ann Arbor Science, Ann Arbor, MI, 1982. pp. 361-372.

Shen presents predictive models for dust and volatile organics emissions from lagoons (Shen Model), and discusses the fate of volatile emissions in the environment in general terms.

LXXXV. Sherman, S., W. Dickens, and H. Cole. Analysis Methods and Quality Assurance Documentation of Certain Volatile Organic Compounds at Lower Detection Limits. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 280-283.

This paper is not useful. It discusses modification of EPA Method 624 to allow lower detection limits for groundwater analysis.

LXXXVI. Skipa, K.J., D.F. Elias, and J.D. Gram. Monitoring and Evaluating Multiple Source Emissions at Hazardous Waste Sites. Presented at the 78th Annual Meeting of the Air Pollution Control Association, Detroit, MI, 1985. 11 pp.

This paper discusses, in a generic form, the issues to be considered in selecting monitoring and modeling approaches to assess the air impacts from a hazardous waste site.

LXXXVII. Smith, P.G., and S.L. Jensen. Assessing the Validity of Field Screening of Soil Samples for Preliminary Determination of Hydrocarbon Contamination. In: Superfund '87: Proceedings of the 8th National Conference, The Hazardous Control Research Institute, Washington, D.C., November 16-18, 1987. pp. 101-103.

This paper compares results from vapor screening of samples in the field using portable analyzers (FID and PID) to results from laboratory TPH analyses. Comparison of the results showed poor correlation indicating the field screening of vapors should not be used as the sole criteria for selecting samples for analysis.

LXXXVIII. South Coast Air Quality Management District. Landfill Gas Emissions: Report of the Task Force, El Monte, CA, 1982.

This report describes task force activities, including sampling of emissions at several landfills in the South Coast Air Quality Management District. Data presented are very limited; sampling methods were headspace over landfill, shallow ground probe, and vent sampling. Site-specific sampling results could possibly be worked up as a case study.

LXXXIX. Springer, C., K.T. Valsaraj, and L.J. Thibodeaux. In Situ Methods to Control Emissions from Surface Impoundments and Landfills. Journal of the Air Pollution Control Association, 36(12):1371-1374, 1986.

This article discusses various control measures to reduce air emissions from landfills and lagoons. Included are air-supported structures, floating objects, shape modification, aerodynamic redesign, oil and surfactant covers, and synthetic membrane covers. The effectiveness and other considerations for use of each method are discussed in general.

XC. St. Clair, A.E., and K.T. Ajmera. Remedial Action at Uncontrolled Hazardous Waste Sites. Environmental Progress, 3(3):188-193, 1984.

This paper describes the feasibility study approach used to develop and select a cost-effective remedial action alternative for the McColl Superfund site in Fullerton, California. Data from the McColl remedial investigation, not presented in this paper, can be used as a case study of baseline emission rate determination.

XCI. Thibodeaux, L.J., and S.T. Hwang. Landfarming of Petroleum Wastes -- Modeling the Air Emission Problem. Environmental Progress, 1(1):42-46, 1982.

This article reviews volatilization from land farming of petroleum wastes, discusses distribution of oil waste in the soil, and presents a gradientless diffusion model for estimating emissions (Thibodeaux-Hwang Model). The article also gives predicted versus measured emission rates for Deldrin.

XCII. Thomas, R.G. Volatilization from Soil. In: Handbook of Chemical Property Estimation Methods, W.J. Lyman, W.F. Reehl, and D.H. Rosenblatt, eds. McGraw-Hill, New York, NY, 1982. pp. 16.1 - 16.50.

This chapter presents a discussion of the theory of volatilization of organics from soil. Thomas presents five models for calculating volatile loss from the soil. The models are: Hartley Model; Hamaker Model; Meyer, Letey, and Farmer Model; Jury, Grover, Spencer, and Farmer Model; and Dow Methods. This work is based on pesticides applied to soil. A decision tree indicating which models apply for varying conditions is included. The models could be applied to sites with known contaminants.

XCIII. Thomas, R.G. Volatilization from Water. In: Handbook of Chemical Property Estimation Methods: Environmental Behavior of Organic Compounds, W.J. Lyman, W.F. Reehl, and D.H. Rosenblatt, eds., McGraw-Hill, New York, NY, 1982. pp. 15-1 to 15-34.

Chapter describes the volatilization process from water. Various methods for estimating volatilization rates are discussed. The Mackay and Leinonen model and others are presented.

XCIV. Thorneloe, S. Summary of Reports Prepared for the Development of Air Emission Standards for Hazardous Waste Treatment, Storage, and Disposal Facilities. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Emission Standards and Engineering Division, Chemicals and Petroleum Branch, Research Triangle Park, NC, 1987.

This report contains annotated bibliographies and contacts for several studies and reports. Most are directly applicable to treatment, storage, and disposal facilities, but some may provide sampling techniques applicable to uncontrolled sites.

XCV. Tucker, W.A., and L.H. Nelken. Diffusion Coefficients in Air and Water. In: Handbook of Chemical Property Estimation Methods: Environmental Behavior of Organic Compounds, W.J. Lyman, W.F. Reehl, and D.H. Rosenblatt, eds. McGraw-Hill, NY, 1982. pp. 17-1 to 17-25.

Chapter discusses molecular diffusion in air and water. Methods are not useful for estimating dispersion in air. Methods may be relevant to uncontrolled sites (i.e., within lagoon or landfill), however, factors such as wind mixing (lagoons) or soil gas flow (landfills) may outweigh molecular diffusion.

XCVI. U.S. Environmental Protection Agency. Letter from J.R. Farmer, Director, Emission Standards and Engineering Division, to D. Kolar, Environmental Counsel, Browning Ferris Industries, dated October 30, 1987, regarding EPA's investigation of techniques for controlling air emissions from municipal landfill facilities.

The U.S. EPA sent a questionnaire to Browning Ferris Industries requesting information on their landfills. The results, described in this memorandum, do not provide information for baseline emissions.

XCVII. U.S. Environmental Protection Agency. Material on RCRA Facility Investigation Guidance (RFI) provided by the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, to Radian Corporation, Sacramento, CA, December 1987.

The material provided includes a Section 12 on Air, Case Study 14: Use of Air Monitoring Data and Dispersion Modeling to Determine Contaminant Concentrations Down-Wind of a Land Disposal Facility, and Case Study 15: Use of Meteorological Data to Design an Air Monitoring Network. This material provides a recommended strategy for characterizing releases to the air. Air monitoring and modeling are discussed in general form. The Field Methods section provides considerable information on available sampling media and appropriate species applications.

XCVIII. U.S. Environmental Protection Agency. RCRA Facility Investigation (RFI) Guidance, Volume III, Section 12, Air and Surface Water Releases. OSWER Directive 9502.00-6C, Office of Solid Waste, 1987.

Provide recommended strategy for characterizing releases to air, which includes characterizing the source and the environmental setting for removal actions at RCRA facilities.

XCIX. U.S. Environmental Protection Agency. Superfund Exposure Assessment Manual. OSWER Directive 9285.5-1, Office of Solid Waste and Emergency Response, Washington, D.C.

Section 2.3 of this manual presents eight equations for predicting short-term and long-term emission rates for landfills with and without internal gas generation, lagoons, landfarms, spills and leaks. Both particulates and volatile emissions are discussed. Equations and discussions are given for determining input variables.

C. U.S. Environmental Protection Agency. Hazardous Waste Treatment, Storage and Disposal Facilities (TSDF) -- Air Emission Models. EPA-450/3-87-026, Office of Air and Radiation, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1987.

Analytical models are presented for estimating air emissions from hazardous waste treatment, storage, and disposal facilities (TSDF). Air emission models have been developed for aerated and nonaerated surface impoundments, land treatment facilities, landfills, and wastepiles (RTI models). Emission model predictions are compared to available field data. This report also includes emission factors for transfer, storage, and handling operations at TSDFs. The models have been assembled into a spreadsheet that is included in this report as floppy diskette for use on a microcomputer. Appendices include a list of physical-chemical properties for approximately 700 compounds and a comprehensive source list of pertinent literature in addition to that cited in the report.

CI. Vandervort, R., C.E. Schmidt, and W.D. Balfour. Surface and Subsurface Gas/Vapor Monitoring Techniques Applied to Environmental Contamination Caused by Petroleum Products and Processing Wastes. Radian Corporation, Sacramento, CA. 12 pp.

This paper discusses the application of surface and subsurface emission rates and vapor concentration measurements for investigating petroleum leaks and hazardous waste site investigations.

CII. Vaught, C.C. A Basic Programming Technique for the Estimation of VOC Emissions from Hazardous Waste Treatment, Storage, and Disposal Facilities. Presented at the 78th Annual Meeting of the Air Pollution Control Association, Detroit, MI, June 16-21, 1985. 9 p.

This paper describes a BASIC program for use on microcomputer. The program uses unspecified predictive models to estimate emission rates for surface impounds, landfills, land treatment, and storage tanks. The program includes a chemical library of required model variables which are accessed by use of CAS numbers, as well as estimation programs for filling data gaps, and adjustments for site- specific temperature conditions. The program was developed in 1985 and may have been updated.

CIII. Vogel, G.A. Air Emission Control at Hazardous Waste Management Facilities. Journal of the Air Pollution Control Association, 35(5): 558-566, 1985.

This article is not related to emissions measurement. It identifies a method to control toxic air emissions from tanks, lagoons, landfills, land treatment facilities, and waste piles. Control cost information is also included.

CIV. Walker, K.A. Air Emissions from Hazardous Waste Treatment, Storage and Disposal. Presented at the 77th Annual Meeting of the Air Pollution Control Association, San Francisco, CA, 1984. 14 pp.

Summarizes OSW's work which is presented in detail by Balfour, Wetherold, and Lewis (1984) included elsewhere is this bibliography. Volatile air emissions at TSDFs were compared for measured versus predictive models.

CV. Weston, R.F. Performance of Remedial Response Activities at Uncontrolled Hazardous Waste Sites (REMII): Draft Remedial Investigation/ Feasibility Study Report for the Bruin Lagoon Site, Bruin Borough, Pennsylvania. U.S. EPA Contract No. 68-01-6939, U.S. Environmental Protection Agency, 1986.

This report presents the results of the remedial investigation performed at a refinery waste lagoon locatei 45 miles north of Pittsburg in Bruin Borough, Butler County, Pennsylvania. Air pathway analyses were performed for determining the health and safety requirements for workers and nearby residences during excavation of the lagoon. Also, sampling and analysis of subsurface soil gas from wells located in the lagoon were performed to determine the soil gas composition, regeneration rates, extent of trapped soil gas within the lagoon and to assist in the assessment of the potential for the release of soil gas into the atmosphere during future excavation.

CVI. Wetherold, R.G., and D.A. Dubose. A Review of Selected Theoretical Models for Estimating and Describing Atmospheric Emissions from Waste Disposal Operations. EPA Contract 68-03-3038, U.S. Environmental Protection Agency, Office of Research and Development, Industrial Environmental Research Laboratory, Cincinnati, OH, 1982. 73 pp.

> This report presents models for determining emissions from landfills, land treatment, lagoons, waste piles, and tanks. Models include both predictive models and indirect measurement techniques. Estimates of model precision and accuracy, and potential sources for model variables are included. Models included are: Hartley Model; Thibodeaux-Hwang Model; Farmer Model; Smith, Bomberger, Haynes Model, Mackay and Leinonen Model; Thibodeaux Concentration Profile; and Thibodeaux, Parker, and Heck Model.

CVII. Wetherold, R.G., B.M. Eklund, and T.P. Nelson. A Case Study of Direct Control of Emissions from a Surface Impoundment. In: Proceedings of the 11th Annual Research Symposium on Incineration and Treatment of Hazardous Waste, Annual Solid Waste Research Symposium, U.S. Environmental Protection Agency, Cincinnati, OH, 1985. pp. 85-92.

> Testing was performed to determine the effectiveness of an inflated flexible dome enclosure in controlling VOC emissions from an aerated wastewater lagoon. Effectiveness was investigated by performing a mass balance of VOCs around the system. The article is not directly applicable to baseline emission estimates.

Wood, J.A., and M.L. Porter. Hazardous Pollutants in Class II Landfills. South Coast Air Quality Management District, El Monte, CA, 1986.

> This report describes sampling for air toxics at several Class II landfills. Landfill gas sampling was performed at 20 sites from vents (when present) and headspace over the site. Ambient air sampling was performed at five sites. Air toxics were detected even though the species cannot be legally disposed of at Class II landfills.

APPENDIX B

CHEMICAL AND PHYSICAL PROPERTIES AFFECTING BASELINE EMISSION ESTIMATES

CHEMICAL AND PHYSICAL PROPERTIES OF THE WASTE MATERIAL AFFECTING EMISSIONS

Property	Effect
Saturation Concentration	The waste will tend to reach equilibrium with the soil vapor. If sufficient waste is present, the equilibrium concentration within the air-filled voids of the soil matrix will reach saturation. Because the rate of emission to the atmosphere is directly proportional to the soil vapor concentration, the emission rate will increase as saturation concentration increases.
Diffusion Coefficient	Compounds with high overall diffusion coefficients will be emitted at higher rates than those with lower diffusion coefficients via increased transport, on a relative basis. The overall diffusion coefficient may be comprised of diffusion through the soil-water interface, soil-air interface, soil, water, air, and soil vapor.
Molecular Weight	Lower molecular weight compounds typically have higher volatilization and diffusion coefficients. Other compound characteristics may predominate. Molecular weight is used to determine diffusion rates in some predictive models.
Partial Pressure of Constituents	High partial pressure increases the emission rate of a species by increasing its soil vapor concentration.
Weight Fraction	An effect similar to partial pressure, it is used as an input to some predictive models. Not as important as Henry's Law constant.
Combination of Constituents	This increases the complexity of the emissions process and determines the emission rate. It may change over time as more volatile species are lost.
Concentration of Waste	Increasing waste concentration increases the emission rate for dilute wastes by increasing the vapor pressure and, therefore, vapor concentration.
Henry's Law Constant	This is used to determine diffusion coefficients. A high Henry's Law constant produces a higher diffusion rate.

(Continued)

Property	Effect
Porosity	One of the controlling factors for diffusion through the soil. Emission rates typically increase with increasing soil porosity. Total porosity, i.e., dry soil, may represent worst-case conditions for predictive models. Air-filled porosity may be more a realistic parameter for many sites.
Adsorption/Absorption Properties of Soil	Soil with high sorption properties will reduce the vapor density of the sorped compounds and, therefore, the emission rate. The effect may be minimal where high waste concentrations saturate the sorption sites. The effect may be reversed causing increased emissions.
Soil Moisture	Its effect varies. High moisture will reduce the air-filled porosity, with pores being filled under worst-case conditions and, therefore, should reduce the emission rate. Moisture may be preferentially adsorped by the soil, releasing volatiles and increasing the emission rate. Drying of soil may increase available sorption sites. Moisture is required for the wick effect.
Wick Effect	Soil moisture may draw waste constituents to the surface through the soil pores. This process can increase the concentration of the constituents at the surface and, therefore, increase the emission rate.
Particle Size Distribution	This affects the total soil porosity and soil pore continuity. Increased soil pore continuity increases the emission rate. A higher percent of fines will typically increase particulate emissions.
Organic Content of Soil	High organic content will increase the sorptive characteristics of the soil and reduce the emission rate. High organic content also will increase microbial action.
Microbial Activity	Its effect varies. It may reduce the emission rate by biological reduction of the waste present. It also may increase the emission rate due to gas formation which carries volatile species to surface.

(Continued)

Property	Effect
Depth of Landfill Cover	Emission rates decrease with increasing depth (thickness) of cover as the diffusion path increases. For an open dump or landfill, the cover thickness is zero.
Compaction of Landfill Cover	Increasing compaction reduces the soil porosity and disrupts continuity of the soil pores, thereby, reducing the emission rate.
Ground Cover	Soil cover, typically vegetation, will reduce particulate emissions by reducing the erodability of the soil. It also will help hold soil moisture, which reduces the air-filled porosity and reduces volatile emissions.
Size of Landfill/Lagoon	The emission rate is directly proportional to the size of the landfill or lagoon.
Amount of Exposed Waste	Emission will increase when waste is exposed at the surface, both due to volatilization and wind erosion.
Water Depth in Lagoon	Water overlying waste will act as a cover. Diffusion through water may control the emission rate.
Aeration of Lagoons	Aeration increases emission of volatile and particulates with increasing volume of air used and/or agitation. The effect is due to air stripping of volatiles and bulk transport of liquid particles.
Temperature	Increasing temperature increases the volatilization rate for organic species and, therefore, the emission rate. Increasing temperature reduces soil moisture, increasing air-filled porosity and the emission rate.
Wind	Wind removes the volatilized compound concentration in the boundary layer over the site, maintaining the driving force for volatilization. Increasing wind speed reduces the boundary layer over the site. WInd causes turbulence within the boundary layer, providing the driving force for surface soil/waste erosion and increasing particulate emission rate.

(Continued)

Property	Effect
Cloud Cover	Increased cloud cover reduces solar heating of the surface and, therefore, the volatilization rate from surface. It also affects wind stability.
Precipitation	Emissions are reduced by reducing the air-filled soil porosity. It may increase landfill emission by displacing soil vapor from soil voids. It may increase surface water and air emissions by floating waste constituents to the surface. Precipitation increases agitation of the lagoon surface, potentially increasing emissions, but it also increases water depth over waste in the lagoon.
Humidity	Increasing partial pressure of water vapor in air reduces the capacity for some types of volatilized material. It may reduce air-filled soil porosity.
Barometric Pressure	Changing barometric pressures cause bulk flow of soil vapor into/out of soil. The overall net effect is to increase the emission rate. The effect increases with frequency and scale of barometric changes.

APPENDIX C

ESTIMATION OF AN OVERALL SOURCE EMISSION RATE USING EMISSION FLUX MEASUREMENTS

C.0 ESTIMATION OF AN OVERALL SOURCE EMISSION RATE USING EMISSION FLUX MEASUREMENTS

This appendix provides guidance on how measured emission fluxes can be used to estimate an overall emission rate for an area source. The information applies to any of the direct emission measurement technologies which are designed to measure an emission flux at a specific point on the emitting surface. A statistical sampling strategy and computation techniques are discussed, and an example calculation is provided.

C.1 Statistical Sampling Strategy

To obtain an overall emission rate for a source, a statistically valid sampling strategy must be developed before samples are collected. Development of this strategy involves the following:

- Division of the total area into zones;
- Subdivision of the zones into smaller units of equivalent area;
- Determination of the number and location of units to be sampled per zone;
- Measurement of emission fluxes from the predetermined grid points; and
- Calculation of an overall emission rate based on the average flux for each zone.

Sampling strategies can be designed to obtain data that will satisfy different statistical criteria. The strategy described below provides an estimated average emission rate within 20 percent of the true mean with 95 percent confidence.

C.1.1 Zones

Based on area source records and/or preliminary screening data (e.g. real-time instrument survey of surface emissions), subdivide the total area source into zones where heterogeneous chemical distribution is exhibited, i.e. areas expected to exhibit comparable emission rates. The zones should be arranged to maximize the between-zone variability and minimize within-zone variability.

C.1.2 Grids

Divide each zone into an imaginary grid with unit areas that depend on zone area size (Z) as follows:

- $Z \leq 500\ m^2$, divide the zone into units with areas equal to five percent of the total zone area;
- $500\ m^2 < Z \leq 4{,}000\ m^2$, divide the zone area into units of $25\ m^2$;
- $4{,}000\ m^2 < Z \leq 32{,}000\ m^2$, divide the zone area into 160 units; and
- $Z > 32{,}000\ m^2$, divide the zone area into units with area equal to $200\ m^2$.

Assign a series of consecutive numbers to the units in each zone.

C.1.3 Sample Size

The number of units to be sampled for the Kth zone (n_K) is calculated based on the area of the zone as follows:

$$n_K = 6 + 0.15\sqrt{\text{area of zone K } (m^2)} \qquad \text{(Eq. C-1)}$$

C.1.4 Sample Locations

The n_K units to be sampled in each zone are selected using a table of random numbers. A unit is selected for measurement only once. Emission flux measurements are then obtained for each randomly selected unit using one of the direct emission measurement techniques.

C.1.5 Zone Emission Rates

After all the unit emission rates are determined, a preliminary mean emission rate for each zone is calculated as follows:

$$\bar{E}_K = \frac{1}{n_K} \sum_{i=1}^{n_K} E_{K_i} \qquad \text{(Eq. C-2)}$$

where: $\bar{E}_K$ = mean emission rate for zone K;

n_K = number of units sampled in zone K;

E_{K_i} = measured emission rate for the i^{th} unit in zone K.

In addition, the variance (S_K^2) and coefficient of variation (CV_K) are calculated for each zone using the following relationships:

$$S_K^2 = \frac{1}{n_K - 1} \left[\sum_{i=1}^{n_K} (E_{K_i}^2) - n_K \bar{E}_K^2 \right] \qquad \text{(Eq. C-3)}$$

$$CV_K = \frac{(100)(S_K)}{\bar{E}_K} \qquad \text{(Eq. C-4)}$$

Before calculating an overall emission rate that represents all the zones measured, the data for each zone must be tested for level of confidence. That is, for the calculated coefficient of variance (CV_K) of zone K, the zone sample size (n_K) must be equal to or greater than the sample size required (n_K) to estimate the overall emission rate within 20 percent of the overall emission rate with 95 percent confidence. The total number of samples (n_K) to be collected for different confidence levels can be calculated as follows:

$$n_K \geq \frac{t_\alpha^2 \ CV_K^2}{\rho^2} \qquad \text{(Eq. C-5)}$$

where a study requires 100 (1-2α) percent confidence that the emission rate estimates will be within ρ percent of the true mean. The parameter t_α is the (1-α) percentage point of a student's t-distribution with N_K degrees of freedom. Tabulated t-values can be found in any book on standard statistical techniques. Recommended values for t_α are listed in Table C-1. The sample sizes required for 95 percent confidence and a 20 percent confidence interval ($\alpha = 0.025$, $\rho = 20$) are listed in Table C-2.

For each zone, the calculated coefficient of variation (CV_K) is used to determine the required sample size (n_K). If $N_K > n_K$, then ($N_K - n_K$) additional units must be sampled in zone K. Additional units are identified using a random numbers table. If additional samples are required to meet the specified confidence limits, then the mean zone emission rate ($\bar{E}_K$), variance (S_K^2), and of coefficient of variation (CV_K) be recalculated using equations C-1, C-2, and C-3. N_K samples are used instead of n_K in the recalculations.

If N_K is significantly larger than n_K (i.e., emission rates from units within the zone are very different), it may be most effective to rezone the entire area using the preliminary measured emission rates as a guide. The new zones will need to be gridded as discussed previously.

TABLE C-1. TABULATED VALUES OF STUDENT'S "t"

s of om*	Tabulated "t" Value**	Degrees of Freedom*	Tabulated "t" Value**
	12.706	21	2.080
	4.303	22	2.074
	3.182	23	2.069
	2.776	24	2.064
	2.571	25	2.060
	2.477	26	2.056
	2.365	27	2.052
	2.306	28	2.048
	2.262	29	2.045
	2.228	30	2.042
	2.201	40	2.021
	2.179	60	2.000
	2.160	120	1.980
	2.145	∞	
	2.131		
	2.120		
	2.110		
	2.101		
	2.093		
	2.086		

es of freedom (df) are equal to the number of samples collected less

ated "t" values are for a two-tailed confidence interval and a ility of 0.05 (the same values are applicable to a one-tailed ence interval and a probability of 0.025).

TABLE C-2. TOTAL SAMPLE SIZE REQUIRED BASED ON THE PRELIMINARY SAMPLE COEFFICIENT OF VARIATION ESTIMATE*

Coefficient of Variation - CV (%)**	Number of Samples Required (N_K) per Zone K
0 - 19.1	6
19.2 - 21.6	7
21.7 - 24.0	8
24.1 - 26.0	9
26.1 - 28.0	10
28.1 - 29.7	11
29.8 - 31.5	12
31.6 - 33.1	13
33.2 - 34.6	14
34.7 - 36.2	15
36.3 - 37.6	16
37.7 - 38.9	17
39.0 - 40.2	18
40.3 - 41.5	19
41.6 - 42.8	20
42.9 - 43.9	21
44.0 - 45.1	22
45.2 - 46.2	23
46.3 - 47.3	24
47.4 - 48.4	25
48.5 - 49.5	26
49.6 - 50.7	27
50.8 - 51.6	28
51.7 - 52.3	29
52.4 - 53.4	30

* Value given is the sample size required to estimate the average emission rate with 95 percent confidence that the estimate will be within 20 percent of the true mean.

** For CVs greater than 53.4, the same size required is greater or equal to $CV^2/100$.

C.1.6 Overall Area Emission Rate

Once the zone emission rates have been determined within the specified confidence limits, the overall area source mean emission rate (E) is calculated as follows:

$$E = \sum_{k=1}^{\gamma} W_K \bullet E_K \qquad \text{(Eq. C-6)}$$

where: E_K = mean emission rate for zone K;

W_K = fraction of the site area covered by zone K (zone area/site area); and

γ = total number of zones sampled.

C.2 Example Calculations

The following example calculations are presented for a hypothetical site contaminated by a spill of JP-4 aviation fuel. The total contaminated area is 1,000 m^2. Other pertinent data and calculations are summarized in Table C-3.

Results from a preliminary emission survey performed with a portable real-time analyzer (organic vapor analyzer) were used to divide the area source into emission zones. The survey indicated that two zones of contamination were present; a small zone with a high concentration of contaminant (250 m^2) and a larger zone with low level contamination (750 m^2).

TABLE C-3. HYPOTHETICAL SITE DATA AND EXAMPLE CALCULATIONS

Data

Total Site Area = 1,000 m^2
Number of Zones = 2
Area of Zone 1 = 250 m^2
Area of Zone 2 = 750 m^2

1

Total number of units = 20 (12.5 m^2)
Number of units to be sampled:

$$n_K = 6 + 0.15\sqrt{area(m^2)}$$

$$n_K = 6 + 0.15\sqrt{250\ m^2}$$

$$n_K = 8$$

sured Emission Flux from Randomly Selected Units	E_{Ki} μg/m^2·min
Unit 4	14.4
Unit 6	12.6
Unit 8	19.6
Unit 13	14.9
Unit 14	10.0
Unit 15	16.6
Unit 19	10.7
Unit 23	11.5
Unit 25	11.4

$$\text{Mean Emission Rate} = E_K = \frac{1}{n_K} \sum_{i=1}^{n_K} E_{K_i}$$

$$E_1 = \frac{121.7}{9}$$

$$E_1 = 13.5 \mu g/m^2 \cdot min$$

TABLE C-3. (Continued)

$$\text{Variance} = S_K^2 = \frac{1}{n_K - 1}\left[\sum_{i=1}^{n_K}\left(E_{K_i}^2\right) - n_K E_K^2\right]$$

$$S_1^2 = \frac{1}{9-1}\left[1724.5 - (9)(13.5)^2\right]$$

$$S_1^2 = 10.5$$

$$S_1 = 3.2$$

$$\text{Coefficient of Variation} = CV_K = \frac{(100)(S_K)}{E_K}$$

$$CV_1 = \frac{(100)(3.2)}{13.5}$$

$$CV_1 = 23.7$$

(from Table C-2) = 8

< n_K (8 < 9)

ne 2

Total number of units = 30 (25 m^2)

Number of units to be sampled:

$$n_K = 6 + 0.15\sqrt{750\ m^2}$$

$$n_K = 10$$

TABLE C-3. (Continued)

asured Emission ux from Randomly Selected Units	E_{Kt} µg/m²·min
Unit 2	0.10
Unit 4	0.25
Unit 7	0.30
Unit 12	0.17
Unit 13	0.18
Unit 17	0.25
Unit 22	0.20
Unit 23	0.21
Unit 25	0.15
Unit 29	0.30

ean Emission Rate = $E_2 = 0.211$ µg/m²·min

ariance = $S_2^2 = \frac{1}{10-1}\left[0.4829 - (10)(0.211)^2\right]$

$$S_2^2 = 4.19 \times 10^{-3}$$

$$S_2 = 0.0647$$

oefficient of Variation = $CV_2 = \frac{(100)(0.0647)}{0.211}$

$$CV_2 = 30.7$$

$_K$ (from Table C-2) = 12

$_K > n_K$ (12 > 10)

(Continued)

TABLE C-3. (Continued)

Emission Rates for 2 additional units:

Additional Units	E_{K_i}, μg/m² • min
Unit 3	0.20
Unit 10	0.15

Recalculated Mean Emission Rate = $\bar{E}_2 = 0.205\ m^2 \cdot min$

Recalculated Variance = $S_2^2 = \frac{1}{12-1}\left[0.5454 - (12)(0.205)^2\right]$

$$S_2^2 = 3.74 \times 10^{-3}$$

$$S_2 = 0.0611$$

Recalculated Coefficient of Variation = $CV_2 = \frac{(100)(0.0611)}{0.205}$

$$CV_2 = 29.8$$

N_K (from Table C-2) = 12

verall Source Mean Emission Rate

$$\bar{E} = \sum_{K=1}^{\gamma} W_K \cdot \bar{E}_K$$

$\gamma = 2$

ne 1: $\bar{E}_1 = 13.5\ \mu g/m^2 \cdot min$

$$W_1 = \frac{250\ m^2}{1{,}000\ m^2} = 0.25$$

(Continued)

TABLE C-3. (Continued)

Zone 2: $\bar{E}_2 = 0.205\ \mu g/m^2 \cdot min$

$$W_2 = \frac{750\ m^2}{1{,}000\ m^2} = 0.75$$

$$\bar{E} = (0.25)(13.5) + (0.75)(0.205)$$

$$\bar{E} = 3.5\ \mu g/m^2 \cdot min$$

To obtain an overall emission rate for the total area, the zones were divided into units according to the criteria specified in Section C.1.2 and assigned consecutive numbers. The number of units to be sampled in each zone was calculated using Equation C-1. This calculation and hypothetical emission rates for each randomly selected unit are summarized in Table C-3. The mean, variance and coefficient of variation were calculated for each zone using Equations C-2, C-3, and C-4.

For zone 1 the level of confidence check indicates that a sufficient number of samples were collected since $N_K < n_K$ (8 < 9). No additional samples were required from this zone. The coefficient of variation (CV_K) for Zone 2 indicates that two additional samples were required ($CV_2 = 30.7$, $N_K = 12$ from Table C-2). The two new zones were sampled and a new mean, variance, and coefficient of variation were calculated using the new sample size ($n_K = 12$). The level of confidence check then indicated that a sufficient sample size ($n_k = 12$) had been collected.

The overall area mean emission rate were then calculated using Equation C-6, as shown in Table C-3. The final result was an overall emission rate of 3.5 $\mu g/m^2 \cdot min$.

APPENDIX D
DESCRIPTION OF SOURCES OF MODEL INPUT DATA

Solid Waste Landfill Survey

The Solid Waste Landfill Survey was initiated by the U.S. Environmental Protection Agency in 1986. Detailed questionnaires were sent to a total of 1,200 municipal landfills; 98 percent responded. The information provided in these responses was complied into a SAS data file by Development Planning and Research Associates, Inc. (DPRA). The information included in this computerized data base includes:

Operations Information

- Owner and operator
- Location
- Number of other municipal landfills in the vicinity
- Shortest distance from the property line/landfill to a residence
- Total area
- Total design capacity
- Total remaining capacity
- Landfill method
- Waste processing techniques
- Quantity of waste from transfer stations
- Quantity of waste from resource recovery stations
- Ratio of waste to cover
- Operational hours

Hydrogeological Information

- Terrain

- Soil type beneath landfill

- Landfill relation to the water table

- Distance from bottom of landfill to bedrock

- Average permeability, porosity, and hydraulic gradient of uppermost aquifer
- Average groundwater flowrate

Waste Composition Information

- Average annual quantity of waste
- Percent of wastes by category (including industrial waste characterization)
- Percent accepting liquids
- Acceptance of liquid solvents
- Segregation of waste types

Design Information--for Closed, Active and Planned Units

- Date opened
- Date last received waste
- Total volume
- Total area
- Maximum height above original grade
- Maximum height below original grade
- Average number of lifts
- Average lift height
- Liner type, thickness, and permeability
- Final cover material, thickness, and permeability
- Type of leachate collecting system
- Volume of leachate collected
- Method of leachate disposal
- Run-on/run-off systems

Monitoring Information

- Gas monitoring and recovery systems
- Air emissions monitoring

National Survey of Hazardous Waste Treatment, Storage, Disposal, and Recycling Facilities -- The National Survey of Hazardous Waste Treatment, Storage, Disposal, and Recycling Facilities was initiated in 1987. The database includes the following type of information:

- Permit data
- Commercial status of landfill
- Operating status
- Expected closure date
- Total capacity
- Surface area
- Liner data
- Quantity of hazardous waste received and generated
- Quantity of non-hazardous waste
- Remaining capacity
- Lab pack waste data
- Expected physical changes to be made
- Waste segregation
- Air pollution controls
- Air emission monitoring systems
- Cover type planned
- Waste restrictions
- Waste composition

National Survey Of Hazardous Waste Generators -- The U.S. Environmental Protection Agency sent this questionaire to a number of hazardous waste generators in 1987. Information requested in the questionnaire included the following.

Operational Information

- Ownership
- Operator
- Total land area
- Longitude and latitude of facility

Waste Composition Information

- NPDES Permit
- Waste water quantity
- Destination of hazardous waste
- Quantity of hazardous waste
- Management and quantity of gaseous hazardous waste
- Generation of explosive materials
- Quantity and management of reactive materials
- Quantity and management of radioactive waste
- Waste minimization programs

Hazardous Waste Management Unit Information

- Any present onsite

- Terrain

- Soil type

- Relation to water table

- Average permeability, porosity, and hydraulic gradient of the uppermost aquifer

- Groundwater flowrate

- Shortest distance of waste management unit to property boundary

Solid Waste Management Unit Information

- Presence of SWMU's
- Number receiving hazardous waste
- Number receiving non-hazardous waste
- Type of unit
- Annual quantity of waste received
- Active or closed
- Start-up date and completion date
- Total quantity waste
- Waste types
- Groundwater monitoring
- Releases of hazardous waste from SWMU
- Waste impoundments
- Waste piles
- Drummed hazardous waste in temporary accumulation areas

Hazardous Waste Information

- Types of waste
- Sources and processes producing waste
- Waste quantity generated per year
- Physical form of waste
- Liquids
- Characteristics

Industrial Subtitle D Survey

The Industrial Subtitle D Survey was initiated by the U.S. EPA and sent to facilities in January 1988. The results of the survey will be used to aid the U.S. Environmental Protection Agency in developing strategies for the management of Subtitle D waste. The information included in this data base is listed below.

Facility Information

- Location
- Permits
- Ownership
- Total area
- Waste minimization
- Wastes generated and managed
- Physical and chemical characteristics of waste
- Waste constituents
- Small quantity generator hazardous waste

Active and Closed Landfill Information -- (Also impoundments, land application units, waste piles)

- Total area
- Total design capacity
- Maximum height above original grade
- Maximum height below original grade
- Average number of lifts
- Average height of lifts
- Liner type and thickness
- Year opened
- Years till closure
- Amount of waste disposed of in landfill
- Wastes present in landfill
- Time spent adding, covering, and compacting waste
- Waste processing
- Landfill method
- Ratio of waste-to-cover
- Percent capacity used
- Leachate collection systems
- Volume of leachate collected
- Management of leachate
- Run-on/run-off systems

Other Waste Management Practices Information

- Incineration: design parameters, control devices, feed composition, and residual management
- Energy Recovery: design parameters, control devices, feed composition, and residual management
- Storage/Treatment tanks: design, process, amount treated, feed composition, and residual management
- Wastewater treatment system: design, process, waste quantity, and composition;
- Recycling refuse: types, quantity, and residual management;
- Offsite management: quantity;
- Underground injection: waste quantity and composition.

Monitoring Information

- Gas systems
- Air emissions
- Soils
- Groundwater
- Surface Water

Hydrogeological Information

- Terrain
- Soil type
- Relation to water table
- Permeability, porosity, and hydraulic gradient of uppermost aquifer
- Average groundwater flowrate

Industrial Subtitle D Telephone Survey -- The Industrial Subtitle D Telephone Survey was also designed to gather information which would aid the U.S. Environmental Protection Agency in developing strategies for the management of Subtitle D waste. The survey began in 1986 and includes the following information:

- Number of active landfills at a facility
- Total area
- Total waste quantity in 1985
- Total design capacity
- Remaining design capacity
- Number receiving offsite waste
- Is offsite waste household waste?
- Also, similar set of questions for surface impoundments, land application units, and waste piles
- Is the facility a small quantity hazardous waste generator (SQG)?
- Does the facility dispose of SQG waste?
- Does the waste management unit receive solvents or metals?

CHEMICAL PROPERTY DATA BASES

EPA Chemical Properties Data Base -- This chemical properties data base is presented in Appendix D of a Office of Air Quality Planning and Standards (OAQPS) report (44). This data base was developed for the use of calculating emission rates from hazardous waste, treatment, storage, and disposal operations with theoretical and empirical models. This data base is available

LOTUS format on a floppy disk and contains data on about 760 chemical mpounds. The data provided in this data base are:

- Chemical name
- CAS number
- Molecular weight
- Vapor pressure at 25°C
- Solubility
- Henry's law constant
- Diffusion coefficient in water
- Diffusion Coefficient in air
- Boiling point
- Coefficients for the Antoine equation for estimating vapor pressure at temperatures other than 25°C
- Cancer unit risk value
- Allowable daily intake in air
- Ratio of biochemical oxygen demand to chemical oxygen demand

The major limitations of this data base are: (1) the physical property data is not complete for all compounds and (2) the properties data provided in the data base represent a mixture of cited values and estimated values.

National Library of Medicine Online Service -- The National Library of Medicine maintains a Hazardous Substances Data Bank (HSDB) that contains data on chemical properties. The HSDB data bank is derived from a core set of standard texts and augmented with information from government documents, technical reports, and journal literature. The data file is maintained, reviewed, and updated on the National Library of Medicine's (NLM) Toxicology Data Network (TOXNET), where it is also searchable. The data bank is organized by chemical, with over 4100 chemical substance records contained in the file. Types of data available include:

- Substance name
- CAS number
- Molecular weight
- Boiling point
- Freezing point
- Specific gravity
- Critical temperature and pressure
- Dissociation constants
- Heat of combustion
- Heat of vaporization
- Octanol/water partition coefficient
- Solubilities
- Vapor density
- Vapor pressure
- Relative evaporation rate
- Viscosity

The HSDB also contains data in an environmental fate/exposure potential file on the following:

- Biodegradation
- Abiotic degradation
- Bioconcentration
- Soil adsorption/mobility
- Volatilization from water/soil

Geophysical Data Bases

The GEMS Geoecology Data Base and the soil temperature data base, available through the National Climatic Data Center (NCDC), can be used to obtain geophysical data for a specific site.

GEMS Geoecology Data Base--

This data base contains county-level data on a variety of environmental parameters including climatic and terrain data. The terrain data includes county soil types from national atlantes, together with some physical and chemical properties of general soil classes. The climatic parameters archived include annual average and monthly maximum and minimum temperatures and monthly precipitation data.

NCDC Soil Temperature Data Base--

This data base is available on computer tape and provides data collected over the period 1967-1982. The primary source of the archived data is daily measurements taken by the Federal Government, State governemnt, and University sponsored Agriculture Research and Experimentation station network. The data are stored by State number, Station Index number, and Division number by daily data, monthly extremes, and monthly average. Each record contains the daily measurements for a particular depth. The major parameters that make up the data file are:

- Depth of soil temperature measurement;
- Soil type; and
- Daily temperature.

Meteorological Data Bases

Meteorological Statistical Array (STAR) data bases and National Climatic Data Center (NCDC) data bases may be useful sources of meteorological information.

STAR Data Base--

Two STAR data sets were identified, the data set created for the Industrial Source Characterization - Long-term (ISCLT) model and the data set created for the Human Exposure Model (HEM). The STAR data set generated for ISCLT is available through the GEMS data management system. This data set was derived from NCDC data and contains data for 394 weather stations in the continental United States. The ISCLT STAR data set provides the following information for each STAR site:

- Frequency of occurrence for different combinations of wind speed, stability class, and wind direction;
- Years of record;
- Annual average mixing height;
- Annual average precipitation;
- Annual average temperature; maximum and minimum temperatures;
- Average morning mixing height;
- Average afternoon mixing height;
- Stability classes and frequency of occurrence;
- Average weighted wind speed for each stability class;
- Average weighted wind direction for each wind speed;
- Average wind speed; and
- Representative wind speeds and frequency of occurrence.

NCDC Data Bases--

The NCDC archives meteorological data collected from cooperative weather stations. Daily and monthly average are available for:

- Maximum and minimum temperature;
- Precipitation;
- Snowfall and snow depth;
- Evaporation;
- Soil temperature;
- Relative humidity;
- Mixing height;
- Wind Speed;
- Wind Direction; and
- Pressure tendency and pressure change.

APPENDIX E

DESCRIPTION OF REMOTE SENSING TECHNIQUES

REMOTE SENSING TECHNIQUES
FOR MEASURING TRACE GASES
IN THE AMBIENT AIR

DRAFT TECHNICAL NOTE

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November 7, 1989

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1.0 INTRODUCTION

The environmental impacts from the release of airborne toxic chemicals is a topic of great interest among air pollution scientists. This interest extends to all types of emission sources including stationary point sources (e.g. incinerator stacks, ground water strippers) as well as area source emissions (i.e., landfills and lagoons). It is important that measurement methods be developed to accurately assess the impact of airborne chemical emissions on the environment. Until now, traditional air sampling/ analytical techniques have been used to characterize emission impacts of airborne toxic chemicals in the environment. While these techniques can provide useful information, very often these methods are unable to provide adequate temporal and spatial resolution due to inherent limitations (i.e., physical, manpower, capital cost, operating cost, etc.). One major limitation is the significant time delay typically encountered between the start of sample collection and the reporting of analytical results.

Significant advances have been made in recent years to develop practical remote sensing methods for measuring trace gases in the ambient environment. The development of cost-effective and very powerful microcomputer technology and reliable medium to low powered gas and semiconductor lasers has made a possible the development of remote sensing techniques which can be used to measure the emission impacts of toxic airborne chemicals in the ambient environment. As a result, several promising remote sensing technologies have emerged, and ultimately may provide scientists with useful tools to conduct environmental assessment studies. Remote sensing could, potentially, allow for rapid screening or in-depth studies of ambient concentrations of airborne toxic compounds. This has obvious implications for the Superfund Program, where there is a need for real-time concentration data for specific analytes for both baseline conditions and during remediation. Such data are essential for making on-site decisions that may affect the health and safety of on-site workers and the surrounding community.

This document briefly summarizes some of the more recent developments in remote sensing technology as it applies to the characterization of emission impacts both area and stationary point emission sources. This document discusses some of the advantages and practical limitations of selected remote sensing technologies. Finally, some general comments and recommendations are provided regarding the future technological development required to advance the development of remote sensing for environmental applications.

2.0 REMOTE SENSING TECHNIQUES

Remote sensing methods can be divided into two general categories. These categories include active remote sensing and passive remote sensing techniques. Active remote sensing typically entails directing a focused beam of energy (usually light energy from a controlled source) through the atmosphere and then sensing the interaction of the beam of electromagnetic energy with the constituent(s) of interest (1). This process usually involves sensing the amount of reflected energy returned to the sensor, through the process of atmospheric backscatter, or by measuring the amount of molecular absorption or neutral absorption (attenuation) that occurs when the reflected energy beam interacts with those constituents of interest.

Passive remote sensing involves two modes of detection (e.g., emission or absorbance). In the emission mode, the target compound(s) emit electromagnetic energy which is sensed directly. In the absorbance mode the target compound(s) react in a manner whereas to change the transmissivity of natural light (e.g., direct sunlight, scenery light skylight, or thermally emitted light). Because uncontrolled light sources are used in conjunction with most passive remote sensing techniques, operational periods are generally limited to periods of sufficient natural lighting.

There are a number of remote sensing techniques which deserve serious consideration for environmental measurement applications. An extensive review of remote sensing methods has been recently compiled by Saeger et.al. (1) for the U. S. Environmental protection agency. A summary listing of those remote sensing techniques which are in common use for environmental measurement applications are given in Table 2-1. The table includes both active and passive remote sensing technologies, which appear suited for measuring trace concentrations of gas or vapors from a variety of emission sources. A brief summary of these methods is provided.

Technique	Region	Parameter(s)	Application	(meters)	Comments
Active Remote Sensing					
Long Path Interferometry					
Fourier Transform IR (FTIR)	IR	Gases and Vapors	Area, perimeter	0.5 to 1 km	Most applications use a telescopic transmitter/ receiver.
Fabry-Perot Interferometry	UV and VIS	Some gases	Stack	Undetermined	High resolution in UV and visible regions. Technique has not been field tested.
Long Path Lidar					
Atmospheric Backscatter Lida	VIS and Near IR	Opacity, aerosol conc., aersol depth.	Area and Stack	0.1 to 15 km	Predominantly used to measure Mie scattering (aerosols and fine dust particles).
Differential Absorption Lida (DIAL)	UV and IR	Atmospheric gases and organic vapors	Area, stack, and perimeter.	0.1 to 8 km.	DIAL can be used in ranging or concentration modes. Technique is useful in eliminating atmospheric interferences.
Raman Scattering Lida	UV and VIS	Atmospheric gases and organic vapors	Area, stack, particle matter, smoke, temperature profiles, and tracking atmospheric dyes and tracers.	0.1 to 1.0 km.	Technique is generally limited to clear sky, nighttime applications. The technique offers limited sensitivity.
Gas Imaging					
Backscatter/Absorption Gas Imaging (BAGI)	IR	Plume ranging and detection.	Stacks, area, perimeter.	0.1 to 0.5 km	Employee DIAL measurement approach. Currently method cannot measure concentration.

(Continued)

Technique	Spectral Region	Measurement Parameter(s)	Measurement Application	(meters)	Comments
Passive Remote Sensing					
Radiometers	UV and VIS	Opacity, velocity, and atmospheric pollutants	Stack	0.1 to 1.0 km	Techniques uses two wavelengths to eliminate atmospheric interferences.
Gas Correlation Spectroscopy					
Non-dispersive GCS	IR	Atmospheric pollutants	Stack perimeter	0.1 to 1.0 km	Typically limited to one compound
Mask correlation Spectroscope	UV and IR	Atmospheric Pollutants	Stack perimeter	0.1 to 1.0 km	Uses skylight as source. Limited to daylight hours.
Interferometry	IR	gases and vapors	Stack	0.1 to 2.0 km	Utilizes Fourier Transform IR

2.1 Active Remote Sensing

Several promising active remote sensing measurement techniques have been developed for environmental measurement applications. Techniques which appear promising for measuring the presence of trace levels of toxic gases and vapors in the atmosphere include:

- Long Path Interferometry;
- Long Path Lidar; and
- Gas Imaging.

Long Path Interferometery

Long path (open path) interferometry can be used in both the active and passive remote sensing modes. As such these devices are useful in assessing the impacts of airborne chemical emissions from a variety of emission sources. There are several types of interferometers used in environmental remote sensing applications (1,2,3,4,5,6,7,8). The most common types are the Michelson interferometer and the Fabry-Perot interferometer.

The Michelson interferometer has replaced most wavelength dispersive spectrometers for applications in the infrared region. This device uses a sophisticated optical arrangement to split incoming radiation into two paths. The two beams are then recombined after introducing a path difference with a moveable mirror. This results in the encoding of a multiplexed spectral inteferogram. A microcomputer is used to perform digitized encoding of the interferogram, and a Fourier transformation of the interferogram is then performed to produce a spectrally resolved output. This technique results in a substantial improvement in spectral resolution and throughput over conventional grating spectrometers. The Fabry-Perot interferometer is used to obtain high resolution and throughput in the ultraviolet and visible ranges. Circular apetures are used instead of slits to improve throughput of these devices.

Long path (open path) interferometery can be used in either the active or passive modes. In active remote sensing applications, the system incorporates either a single ended or double ended telescopic transmitter/receiver configured to measure the absorbance of features of those constituents of interest. A coaxial telescope arrangement is used to direct a line of site beam of infrared light across an area of concern. In a double ended configuration, the light source is mounted on a tripod [illegible] some other mounting device at some fixed path distance from the receiver optics/interferometer as shown in Figure 2-1. This arrangement can be modified by the addition of collimator optics such that the transmitter and receiver are housed in the same unit, and corner cube retroflectors are then used to reflect the transmitted IR beam back to the receiving telescope. The latter design offers several advantages over the double ended design in that the retroreflectors are much more portable and easier to align. Both arrangements can be configured to permit multiple reflectance targets to be used to extend path coverage over a wider area.

Typically, long path Fourier Transform IR (FTIR) is used in the absorbance mode to make horizontal measurements over distances of 0.01 to 2.0 km. These devices are used to gather path averaged concentration measurements for a variety of gases and vapors that have moderate to strong absorbance features in the infrared region. Because these systems employ an interferometer and sophisticated signal processing computer hardware and software, they can be programmed in either a spectral search mode or used to selectively scan selected regions of the infrared spectrum if the absorbance frequencies of the compounds of interest are known.

Long path FTIR is capable of measuring path integrated concentrations in the low ppm-meter range. The ultimate sensitivity will depend on the width the pollutant plume and distribution of the gas or vapor molecules along the directed path. In most instances it is convenient to relate the path integrated concentration measurements in terms of one meter closed path cell. System calibrations can be performed in the field by inserting closed gas cells in a specially designed mount and directing the light source through the cell.

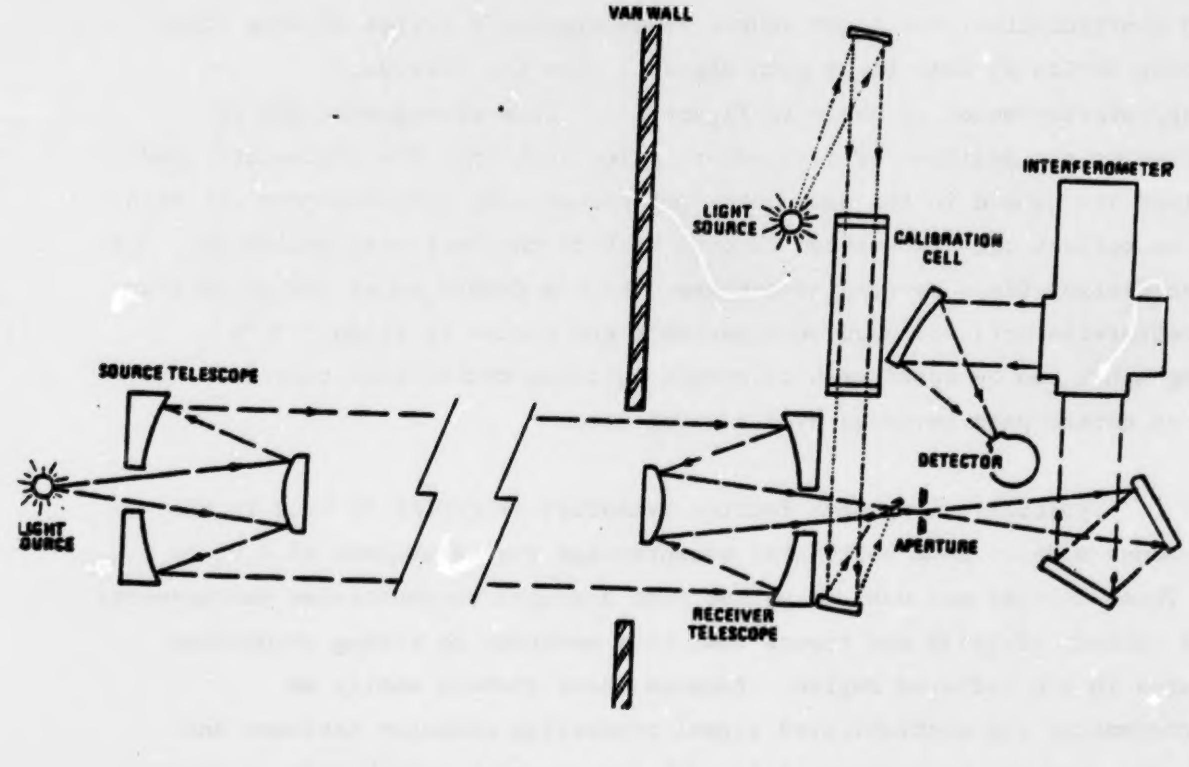
VAN WALL
INTERFEROMETER
LIGHT SOURCE
CALIBRATION CELL
SOURCE TELESCOPE
DETECTOR
LIGHT SOURCE
APERTURE
RECEIVER TELESCOPE

Figure 2-1. Optical Configuration for Long Path FTIR.

Long path FTIR is quite versatile because it can be used to obtain both qualitative and quantitative information regarding the presence of compounds which exhibit strong absorbance features in the infrared spectrum. Spectral libraries exist for a large number of gases and vapors, and software programs designed to perform spectral matching for complex matricies are available. This latter feature is very important if the system is being used near emission sources which have not been previously characterized. However, the technique is subject to atmospheric and chemical interferences (i.e., carbon dioxide, carbon monoxide, water vapor, etc.), and may not possess the sensitivity or selectivity to accurately characterize extremely low concentrations of gases and vapors. Spectral subtraction and data manipulation techniques are used to minimize the effects of atmospheric and chemical interferences (4). However, due to inherent limitations in the sensor design, it may not be possible to completely eliminate atmospheric or chemical interferencies using reference path and spectral subtraction techniques.

Long path FTIR has been used to effectively characterize fugitive emission sources from surface impoundments and landfarming operations. Additionally, there are commercially available, open path FTIRs used in perimeter monitoring applications. In the spectral search mode, long path FTIR can be used to screen for the presence of infrared active species. Once compounds of interest are detected, the system can then be placed in a scan mode which will simultaneously scan for several compounds of choice.

Long Path Lidar

The development of laser technology has made possible the development of long path Light Detection and Ranging (Lidar) techniques for environmental and atmospheric measurement applications. Bordonali et.al. (2) provide an excellent theoretical overview of Lidar based sensing techniques. A number of Lidar methods have evolved. These include atmospheric (Mie) backscatter, Differential Absorption Lidar (DIAL), fluorescence Lidar, Raman backscatter Lidar, wedge Lidar, and Doppler Lidar. These methods have been used in the following applications:

- Area and perimeter monitoring of airborne chemical emissions from area sources;
- Measurement of pipeline leaks and other stationary point sources, and fugitive emissions;
- Monitoring of trace concentrations of vapors and gases which participate in photochemical reactions;
- Measurement of atmospheric parameters (i.e., temperature and wind velocity); and
- Validation of pollutant transport models.

Of the Lidar methods cited, atmospheric backscatter and DIAL have been demonstrated to be effective in assessing impacts of airborne chemical emissions from area and stationary point sources. Depending on the particular application, these types of measurement techniques offer the ability to characterize the temporal and spatial impacts of air emission sources.

Atmospheric Backscatter Lidar

The most common and effective backscattering Lidar technique involves the measurement of Mie scattering. In this application the transmitter/receiver are collocated. The use of lasers permits the use of intense monochromatic sources of light energy which are tunable and can be emitted as continuous waves (CW) or in short duration pulses. The latter permits useful range information to be obtained by measuring the time interval over which backscattered light energy is returned to the receiver (2). When a light beam is transmitted through the atmosphere a portion of the transmitted light is scattered in many directions when it interacts with atmospheric constituents. A portion of the transmitted light energy is returned along the axis of directed beam by a process known as backscatter.

There are three scattering processes which occur. These are Mie, Rayleigh, and Raman scattering. Mie scattering occurs when the parameters of interest (i.e., aerosols, dust, water droplets, etc.) are the same size (diameters) as the wavelengths of the incident light. Mie scattering is not wavelength dependent, and untuned lasers can be used to measure aerosol concentration, particulate emissions, and opacity. Sensors, which operate based on the measurement of Mie scattering, employ lasers which operate in the infrared and visible range (1). Pulsed Mie backscattering sensors are able to determine both concentration, plume opacity and ranging information. For the most part these types of devices have been used to characterize emissions from power plant plumes. In these applications, the plume measurements are referenced to clean air Lidar returns. These types of sensors are capable of remotely measuring particle and aerosol concentrations at ranges of 0.1 to 15 km. However, these devices are not as sensitive as other remote sensors which use optical reflectors to increase throughput of light energy from the controlled source.

Differential Absorption Lidar (DIAL)

Differential Absorption Lidar (DIAL) relies on the wavelength dependence of those gases of interest to obtain quantitative concentration data for specific analytes of interest. DIAL remote sensing systems typically employ a laser(s) tuned to two different wavelengths. DIAL devices employ either a single or double ended transmitter and receiver configurations. In most cases, the single ended system is preferred due to the increased sensitivity due to path doubling when reflectance targets are employed.

The DIAL technique involves tuning one laser to a wavelength for which the compound of interest contains a strong spectral absorbance feature (wavelength "on"), and the second laser tuned to a wavelength in a region of low absorption (wavelength "off"). The technique of simultaneous one "on" and one "off" sensing permits DIAL systems to be operated under a variety of conditions and virtually free of other atmospheric interferences (aerosols, water vapor, dust, fog, snow and water droplets). In some system designs, it is possible to accomplish the same effect by tuning a single laser to two different wavelengths. Thus, by comparing the attenuation in the intensity of the two signals (e.g. differential absorption) it is possible to detect the presence of a particular compound of interest. This technique has been particularly useful in measuring those gases and vapors which have strong absorption features in the infrared and ultraviolet ranges.

The DIAL technique can be configured to measure the differential absorbance of light returned to the receiver by the distributed reflectance of aerosols and molecules. A modification of this technique involves using topographical reflectors (hills, walls of buildings, etc.) to reflect the light beam to the receiver. If the system is configured with pulsed lasers in the UV visible range, it is possible to not only obtain concentration data, but also obtain ranging information to determine the location and path width of the plume. Typically, lasers in the infrared do not have sufficient power to obtain effective ranging information. Figure 2-2 illustrates the use of DIAL sensors in both the distributed reflectance and topographical reflectance modes.

Figure 2-3 illustrates a DIAL system developed by TECAN REMOTE which employs cornercube retroflectors in a topographical reflectance mode (4). In this configuration the corner cube reflector acts as a man-made topagraphical reflector with extremely high reflectance efficiency. This approach results in greater signal reflectance than other natural or man made topographical reflectors (i.e., walls, buildings, etc.). It is important to note that when topographical reflectors are used, the resulting measurement represents a path averaged concentration measurement over the entire path, and ranging measurements cannot be effectively obtained. The use of cornercube reflectors permits lower powered lasers to be used with minimal degradation in sensor performance. This is extremely important from the standpoint of eye safety. Lasers operated in the IR range above 1.4 um. and in the UV range below 0.4 um can present eye safety dangers, and may restrict their use in certain

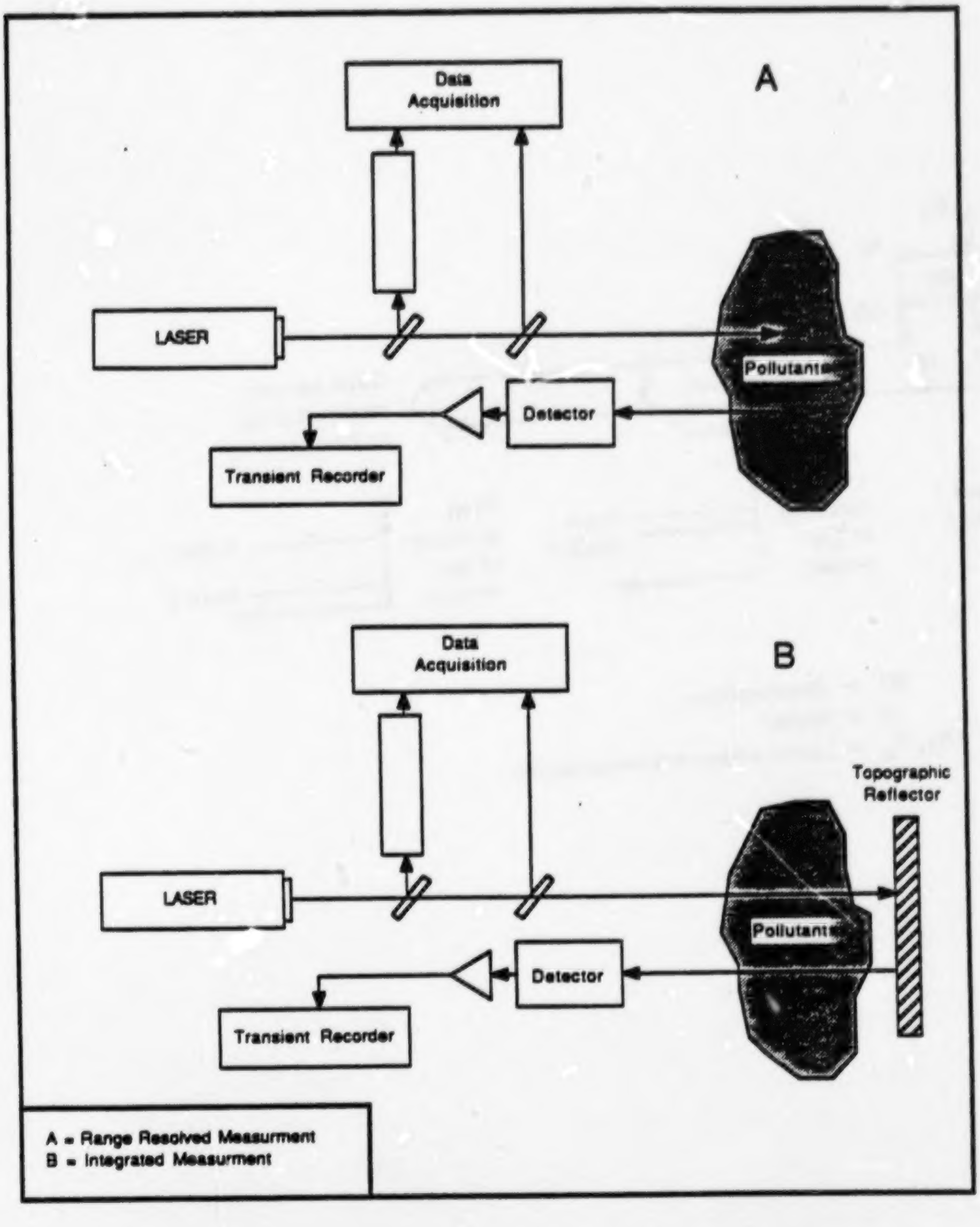
Data Acquisition
A
LASER
Pollutant
Detector
Transient Recorder
Data Acquisition
B
Topographic Reflector
LASER
Pollutant
Detector
Transient Recorder
A = Range Resolved Measurment
B = Integrated Measurment

Figure 2-2. Differential Absorption Lidar Operated in A Range Resolved or Topographical Refectance Mode

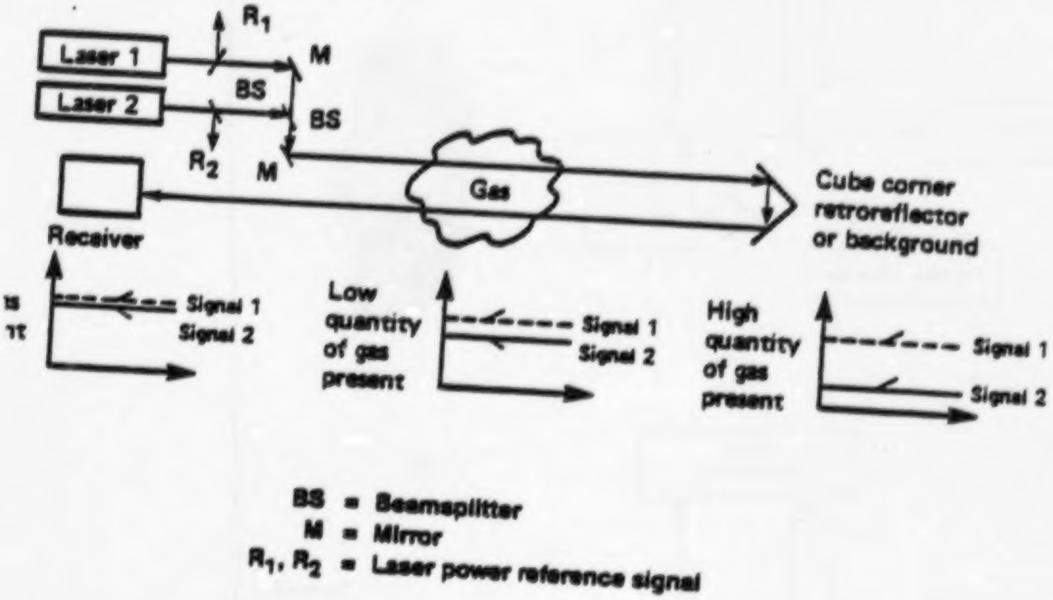
R1
Laser 1
M
Laser 2
BS
BS
R2
M
Gas
Receiver
Cube corner retroreflector or background
ts
nt
Signal 1
Signal 2
Low quantity of gas present
Signal 1
Signal 2
High quantity of gas present
Signal 1
Signal 2
BS = Beamsplitter
M = Mirror
R1, R2 = Laser power reference signal

Figure 2-3. Basic DIAL Lidar System Configuration.

instances (i.e., populated areas, workplace area, etc.). The effective path range over which measurements can be made varies depending on system configuration and application. Pulsed lasers can provide effective measurements over a range of 5 km and continuous lasers can be used at effective ranges up to 1 km.

Various types of lasers can be used to emit emission lines ranging from 0.27 to 337 μm. There are four classes of lasers which are in widespread use. They are distinguished based on the lasing medium, and include: gas lasers, liquid lasers, semiconducting lasers, and dielectric crystals and glasses (10). Those lasers which emit laser lines in the ultraviolet and infrared spectrum are the most popular for use in remote sensing applications involving the trace measurement of gases and vapors. One of the most effective lasers used in commercial DIAL applications is the CO_2 laser. This laser emits 60 emission lines between 9 and 12 μm.

It is important to note that differential absorption techniques can also be used with a combination of blackbody radiation sources and narrow bandpass filters (9) to obtain results which are functionally comparable to conventional DIAL techniques which use laser sources. Figure 2-4 illustrates an example of an infrared differential absorption system developed by TECAN REMOTE. This double ended system, is limited in the effective range over which measurements can measurements can be made (~200 meters). However, it offers the ability to sequentially measure more than one compound using a filter wheel and chopper arrangement to alternate between absorbing and non-absorbing frequencies. This represents a practical advantage over conventional DIAL systems which are typically designed to measure only one compound at a time.

DIAL techniques are effective in characterizing chemical emissions from stationary point sources, fugitive emissions from area sources. These types of sensors offer reasonable effective ranges over which measurements can be made, and are designed to minimize atmospheric interferences. These systems can be configured for use in mobile labs or stationary shelters

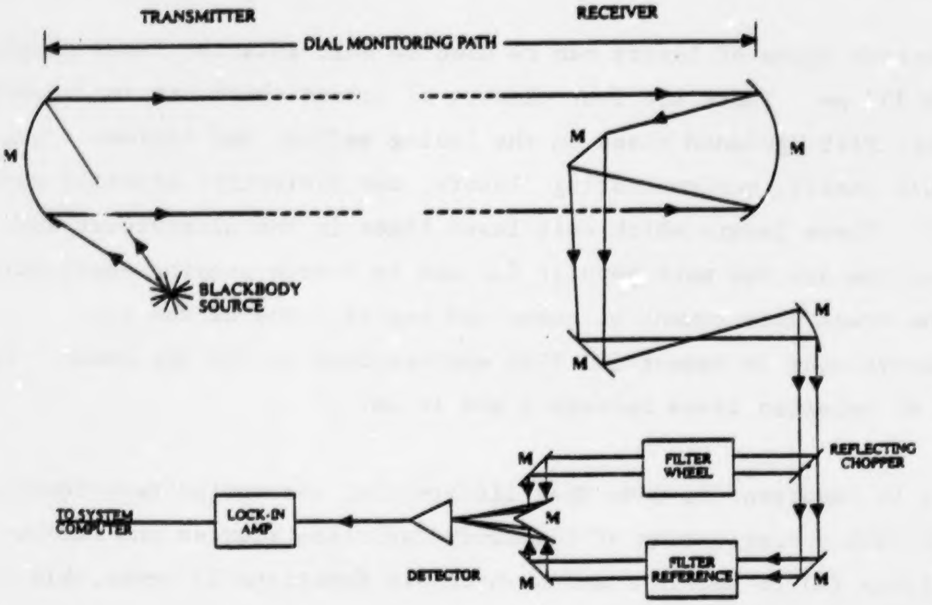
TRANSMITTER
RECEIVER
DIAL MONITORING PATH
M
M
M
BLACKBODY SOURCE
M
M
REFLECTING CHOPPER
FILTER WHEEL
M
M
TO SYSTEM COMPUTER
LOCK-IN AMP
DETECTOR
M
FILTER REFERENCE
M

Figure 2-4. Differential Absorption Lidar Using A Non-Laser Source.

This permits both transient or semi-permanent/permanent monitoring to be performed for both stationary and area monitoring source characterization applications. While the systems are sensitive in the low to sub-part-per-million meter range, the usefulness of these techniques as screening tools to assess potential health hazards depends, to a large part, on the source strength and other emission source characteristics. As such, these methods may not be as sensitive as integrated point monitors in some applications. The same also holds true for long path interferometery techniques. Furthermore, it is important to note that it is possible to select wavelengths where more than one compound will absorb, thus increasing the potential for chemical interferences. In some cases the absorption characteristics of other atmospheric or chemical interferents are such that either positive or negative interferences can occur, thereby making data interpretation difficult. Therefore, there may be times when the use of this technique may result in the measurement of erroneous data. Physical obstructions (i.e., animals, man, man-made objects, etc.) are easily detected and the measurement output can be flagged accordingly.

Gas Imaging

A sensing technique which involves the use of Backscatter/ Absorption Gas Imaging produces a visible image of invisible gas plumes on a video monitor (1). This technique measures the differential absorption of backscattered radiation at the absorption wavelength of interest. Sophisticated signal processing techniques are used to display a real time image of the plume on a video monitor. A laser beam is directed to points within the plume and outside of the plume to measure the amount of radiation which is differentially absorbed by the gas species of interest. This system has been used primarily in imaging gas plumes from stationary emission sources, but can be used in other applications. Carbon dioxide gas lasers are used as a laser source to produce emission lines in the infrared range. This particular technique when coupled with other sophisticated data processing techniques can be used to estimate plume volume, plume height, and plume velocity. This particular technique has not been used to measure plume concentration.

2.2 Passive Remote Sensing

Several passive remote sensing techniques have been developed to measure atmospheric parameters (i.e., temperature, water vapor, and atmospheric gases), and chemical measurement parameters. In general these devices have been used from satellite, aircraft and mobile ground based platforms and for stationary stack measurement applications. These devices include radiometers, gas correlation spectrometers, and interferometers. A brief description of these types of remote sensing techniques follow.

Radiometers

Radiometers are non-dispersive measurement devices which have been used over a wide spectral range including UV, visible and IR regions. These devices are designed to measure electromagnetic radiation over a specified spectral region (10). A series of interference filters can be use to isolate the spectral regions of interest. Radiometers are low resolution devices. The most common use of radiometers has been to measure temperature, opacity, plume velocity, and gas concentration (in limited applications). As such, these devices are rather limited in the ability to selectively monitor trace gas concentration of airborne chemicals for environmental measurement applications. However, they do have some application in obtaining infomration (i.e. temperature, opacity) to track the transport of pollutants form specific sources.

Gas Correlation Spectroscopy

Gas correlation spectroscopy simply measures the degree of correlation between the spectrum of radiation emanating from the target gas emissions compared to a known spectrum (1). This technique is extremely sensitive and selective, and can be used to sense passive emissions from a target gas over a large area. There are two basic types of gas correlation spectrometers: non-dispersive and dispersive gas correlation techniques. Most correlation spectrometers operate in the infrared spectrum.

Non-dispersive gas correlation spectrometers use a gas cell filled with the component of interest to mask the incoming radiation (1). In most designs, the spectrometer consists of two cells (e.g. sample and reference). The sample cell is filled with the gas constituent of interest. The reference cell is either evacuated or filled with an inert gas. The incoming radiation is alternated between the two cells (e.g., reference and sample cells). This is accomplished typically by chopping the incoming radiation which is directed through each cell. In the absorbent mode, the incoming radiation is selectively absorbed by the target gas of interest. Due to differences in the intensity of the incoming radiation and the absorption spectra of the gas in the sample cell, there is an attenuation in the radiant energy passing through the sample cell. Thus, the difference in the modulated signal is inversely proportional to the gas concentration of the target constituent in the atmosphere. In the emissions mode, the gas concentration is proportional to the concentration of target gas concentration in the atmosphere.

In the dispersive mode, the incoming radiation is dispersed into its spectrum (typically using an optical grating). The dispersed radiation is then superimposed on a machined mask positioned at the entrance to the detector. The mask is machined such that the slits in the mask correspond to the wavelength minima. The mask is specific to the spectrum of the target gas of interest. The part of the incoming spectrum which matches the mask causes an oscillation in the detector. The portion of spectrum of the incoming radiation that does not match the mask causes a low amplitude variation in the detector signal. The concentration of the target compound of interest is proportional to the difference in the detector output (max vs. min) referenced to the average.

Gas filter correlation techniques and mask correlation spectrometers are typically designed to measure only one compound of interest. This limits the overall utility of the method, unless the component of interest is an atmospheric tracer which can be used to estimate the concentration of other compounds of interest.

Interferometry

As previously mentioned, Fourier Transform interferometers can be operated either as active of passive remote sensors. In the passive mode, the infrared emissions can be detected using long path FTIR techniques. The sensitivity in the emissions mode is typically on the order of a factor of 10x less than when used in the absorbance mode. However, in most applications involving the measurement of gas concentrations from stationary point source plumes at elevated temperatures, it is necessary to determine the temperature from the emission spectrum (7).

3.0 APPLICATION OF REMOTE SENSING TECHNIQUES

Traditionally, direct source sampling techniques have been used to estimate the emissions from stationary point sources (i.e., boiler stacks, flares, tail gas treatment systems, incinerators, process vents, etc.). These direct sampling techniques include a variety of integrated sampling and continuous emissions monitoring devices (i.e, extractive and in-situ monitors). Similarly, fugitive emissions from industrial sources, chemical processes, and various types of treatment, storage, and disposal facilities (i.e., landfills, surface impoundments, landfarms, aeration lagoons, etc.) have been characterized using direct integrated sampling methods as well as arrays of continuous measurement devices. While these devices are generally effective in assessing air emission impacts, they can be quite costly in terms of man-power, analytical costs, and/or routine operational costs. Furthermore, the number of samples required to adequately characterize air emission impacts may in some instances be cost prohibitive.

The use of remote sensing techniques may offer a more attractive alternative for conducting both screening and routine surveillance monitoring. This need is particularly critical around Superfund sites which are either in the remedial investigation or remediation stages. Emissions of airborne toxic chemicals from these sites pose a potential threat to both the workers on site, and to local citizens who live and work in close proximity to these sites. Additionally, the chemical manufacturing and petroleum refining industries have shown interest in the applicability of remote sensing technology to detect routine releases of airborne chemical emissions which are reportable under SARA Title III. There is also interest in developing perimeter and in-plant monitoring systems which can provide an early detection of process malfunctions for emergency response purposes. This section examines some practical applications of remote sensing technology in assessing the emission impacts for a variety of trace gas constituents.

For the purpose of this discussion, the examination of remote ing techniques will be limited to those which are capable of measuring e levels of airborne chemicals which might be emitted from a variety of ionary point sources and area sources. A discussion of the practical ications of these technologies as well as the current limitations is sented. These applications include the following:

- Point source monitoring (i.e., boiler stacks, flares, incinerators, process vents, tailgas treatment systems, etc.);
- Screening of fugitive emissions from stationary area sources (i.e., landfarms, surface impoundments, wastewater treatment systems, landfills, etc.); and
- Routine Perimeter Surveillance Monitoring (i.e., chemical plants, refineries, TSDF's, etc.).

3.1 Point Source Monitoring

A number of remote sensing techniques have been developed which are designed to measure the concentration of various gases emitted from stationary point sources (6,7) . To date these methods have been evaluated from sources including: utility boilers, flares, cement plant kilns, etc. Both active and passive remote sensing techniques have been used to characterize plume temperature, opacity, particulate loading, and the concentration of combustion gas products and other pollutants (i.e., NO_2, NO, CO, CO_2, HCL, NH_3, HF, SO_2, and H_2CO. This technique is amenable to measuring a variety of organic and inorganic compounds which exhibit strong absorbance features in the infrared spectrum.

The most common remote measurement systems which have been used to evaluate airborne chemical emissions from stationary point sources include:

- Long path FTIR operated in both the emissions and absorbance modes;

- Gas filter and mask correlation spectroscopy; and
- Differential absorption Lidar.

The U. S. Environmental Protection Agency has conducted extensive experiments to evaluate long path FTIR. The remote optical sensing emissions (ROSE) system developed by EPA (3-8), is a good example of a mobile remote sensing system based on the use of a commercially available Fourier Transform infrared system. The ROSE system consisted of a Nicolet model 7199 FTIR which was van mounted. The system was configured with a Dall Kirkham f/5 telescope. A diagram of the system is shown in Figure 3-1. This system is capable of measuring both in an emissions measurement mode (passive), or in an absorbance mode (active) using cross stack sampling techniques.

In the cross stack mode, ports are installed in the stack, and a collimated beam is aimed through the stack and reflected back to the receiver located in the mobile van at the base of the stack. In the cross stack mode, the system is capable of obtaining sensitivities on the order of 1 ppb. In the emissions mode the receiver telescope is use to sense the IR emissions signatures of pollutants of interest which exit the stack. The sensitivities for most pollutants of interest is on the order of 1 ppm. In the emissions mode, the FTIR system is particularly sensitive to plume temperature. Thus, estimates of plume temperature are needed to correct the concentration measurement data. Temperature measurements are estimated based on measuring the spectral radiance of two different CO_2 lines. Of the two methods, the cross stack measurement method is more sensitive and accurate than the emission measurement mode. However, the logistics associated with the emission measurement mode is more convenient, and yields acceptable accuracies (+- 20%) when compared to extractive sampling techniques. Systems such as this cost on the order of $200,000 to $300,000.

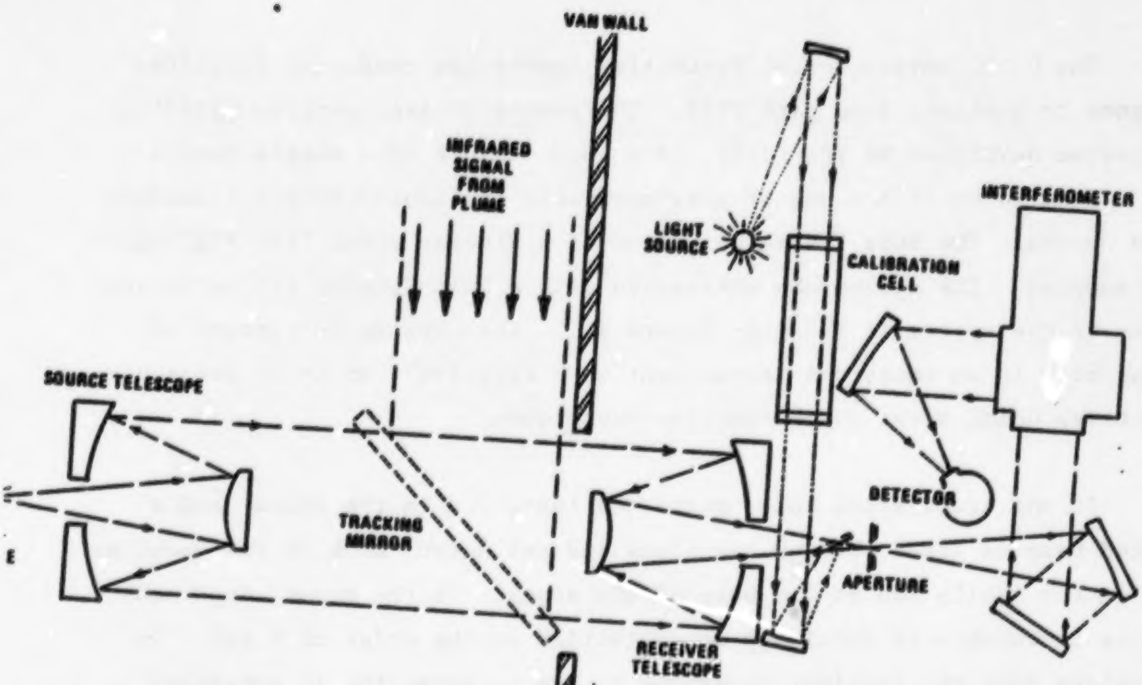
VAN WALL
INFRARED SIGNAL FROM PLUME
INTERFEROMETER
LIGHT SOURCE
CALIBRATION CELL
SOURCE TELESCOPE
TRACKING MIRROR
DETECTOR
APERTURE
RECEIVER TELESCOPE

Figure 3-1. EPA Rose Infrared Spectrometer System.

Another useful tool which can be used to measure gas concentrations from stationary point sources involves the use of gas filter correlation and mask correlation spectrometers. These techniques have been previously described in Section 2. The Barringer COSPEC is an example of a mask correlation spectrometer (which can be used in either a passive or active or passive mode. The COSPEC has been commercially developed to measure either NO2 or SO2. In the active mode the system is reported to have sensitivities of approximately 2 ppb over a range of 300 meters.

In the passive mode, the COSPEC system has been used in a variety of plume tracking modes. In the look up mode, it is possible to track plumes from stationary sources for long distances. The system is easy to use, it is rugged, and can be operated by semi-skilled technicians. In the emissions mode, the performance of the device is subject to drift based on the changes in the source spectra (1), thus is limited to daylight use only. Furthermore, these devices are also are sensitive to changes in the plume temperature. The sensitivity in the passive mode is between 2-5 ppm-meters. The cost of the COSPEC ranges from $30,000 to $50,000 depending on options. Gas filter devices (which operate in a similar fashion) are also commercially available.

Differential Absorption Lidar can be used for measuring a variety of gas species and can be operated in an emission or absorbance measurement mode. These devices can be used to measure UV, VIS, and IR active species. Since most DIAL systems employ the use of lasers, the specific compounds of interest which can be detected will be dependent primarily on the emission lines of the laser. These devices can be employed in a similar manner to the long path FTIR, and can be used to perform range resolved, cross stack measurements, and or used with topographical reflectors. Because the DIAL systems are active remote sensing devices, these systems can be used both during the day and at night, and have the ability to minimize atmospheric and chemical interferences by use of differential absorption.

While DIAL systems are very effective measurement tools, they do have certain limitations. It must be noted that the current commercially available systems are capable of measuring only one compound at a time, and must be manually tuned for each compound of interest. Furthermore, other compounds which have absorption features at the designated absorption minima of a compound of interest, can interfere (false negative) and result in erroneous measurement results.

Most commercially available DIAL systems have sensitivities and selectivities which are comparable or better than long path FTIR's. The cost of these systems are also generally comparable with that of FTIR's and range from $100,000 to $200,000. These costs are dependent on the application (stationary vs. mobile), and types of features desired with regard effective range, data processing capabilities, and data display.

Most remote sensing devices which measure the concentration of pollutants emitted from stationary sources are housed in mobile vans or on lightweight tripods, and can easily be move to various vantage points to conduct measurements. Some systems like the COSPEC device and other gas correlation spectrometers can also be mounted in mobile platforms (i.e., vans, airplanes, helicopters, etc.) and measurement results can be obtained while the platform is in motion. This is particularly desirable for tracking plumes from a point source, identifying "hot spots", or screening for gas leaks from pipelines, etc.).

The applicability of using remote sensing techniques for measuring emissions from stationary point sources will depend on a number of factors, such as the characteristics of the source, site characteristics, meteorology, and the limitations associated with the design and operation of the remote sensor. Factors include:

Source Characteristics

- Pollutant concentrations;
- Plume width;
- Plume temperature;
- Plume exit velocity;

Site Characteristics

- Physical Obstructions which limit field of view;
- Objects which might interfere with plume dispersion (i.e., building wave effects);
- Accessibility of convenient vantage points to allow the set-up and operation of remote sensing systems;

Meteorology

- Meteorological conditions that effect plume dispersion;

Limitations in Sensor Design

- Variations in measurement results for those devices which require natural lighting;
- Field of view of the sensor;
- Selectivity and sensitivity;
- Number of compounds which can be measured;

- Interferences (atmospheric or chemical);
- Logistics required to support measurements (available power, need for cryogens to cool some detectors, physical space requirements, etc.);
- The need for environmental enclosures required to filter out vibration, and maintain constant temperature and humidity; and
- Overall complexity.

The methods described above have been shown to yield results comparable (+20% to 30%) to extractive point sampling techniques (i.e. long path FTIR, gas correlation, spectroscopy, and DIAL).

3.2 Area Source Monitoring

The use of remote sensing devices to assess impacts of emissions from stationary and other area sources (i.e., chemical process units, wastewater treatment systems, landfarms, landfills, waste handling facilities, etc.) is an area of great interest. These devices offer the following potential advantages:

- Rapid assessment of toxic airborne chemicals over a wide area;
- Real-time assessment temporal and spacial variation of emissions on ambient air quality; and
- Cost effective alternative to integrated point source monitoring.

There are several remote sensing techniques which offer the ability to assess the ambient emission impacts from a variety of stationary and area sources. Both active and passive sensing techniques have been used. They include: long path interferometry, Lidar, DIAL and gas correlation spectrometers. These operation of these devices have previously been described.

EPA has recently evaluated several types of remote sensing techniques for conducting pre-remedial air investigations near waste sites (4). The purpose of these investigations was to assess the feasibility of using remote sensing techniques to screen for air emissions from these sites. In this preliminary investigation, three types of remote sensors were used. They were long path FTIR, long path UV, and differential absorption Lidar.

The long path FTIR system consisted of Nicolet model 730 equipped with a double ended Cassgrain receiver and transmitter. The energy source consisted of a 100 watt halogen lamp and infrared globar source. A mercury-cadmium-telluride liquid-nitrogen cooled detector was used to operate over a range from 700 to 1400 cm-1. The system was equipped with a microcomputer data system to process and display the measurement results from the sensor. The receiver optics and interferometer were located in a mobile van, and the transmitter scope was tripod mounted at fixed distances from the receiver/interferometer. The system was operated in the absorbance mode.

The UV system consisted of long path UV system designed and built by the University of Denver. The system consisted on a single ended transmitter/receiver. The system contained UV source (xenon arc lamp), focusing mirror, retroreflectors, beam splitter, and photodiode array monochromator. The system was used in both a qualitative and semi-quantitative mode to measure a variety of aromatic and other compounds with absorption features in the UV range.

The differential absorption Lidar system was manufactured by TECAN REMOTE, and consisted of a dual CO2 laser each capable of generating emission lines over the range of 9 to 11 mircrometers. The LASERSAFE system contained a photoconductive, mercury-cadmium-telluride detector, and lock-in amplifier for signal processing, and optics were housed in a single ended transmitter/ receiver design. Retroreflectors positioned at a fixed distances from the transmitter/receiver unit were used to reflect the infrared beams from the analytical and reference lasers tuned in a one "on" and one "off" differential absorption mode.

In EPA's limited evaluations studies, the IR and UV systems have been used to monitor air emissions upwind, downwind, and cross wind of waste sites. The purpose of these investigations was to assess air emission impacts of toxic airborne chemicals emitted from hazardous waste sites. The Hazard Ranking System (HRS) model was used to rank sites for possible inclusion on the National Priorities List (NPL). The use of remote sensing offers the potential for reducing the time and effort required to complete investigations of this type. A total of 21 contaminants were designated for evaluation based on previous investigations of the test sites.

The long path FTIR and UV systems were used in a qualitative mode to first identify various volatile organic compounds emitted from each site, and then the DIAL system was used to conduct quantitative assessments of those contaminants in the DIAL library. The long path FTIR and UV systems were also used in a semi-quantitative mode to determine path averaged concentrations of toxic airborne chemicals at locations positioned both upwind, downwind, and cross wind of the designated site areas. Because of shifting winds at the test site, it was not always possible to position the equipment simultaneously upwind and downwind of the designated facility.

The results of the limited evaluation suggest that remote sensing can be used as an effective screening tool (at least in limited applications) to screen for the presence of fugitive airborne toxic emissions from area sources. However, it must be recognized that no comparative data was obtained using alternative point sampling methods, and therefore no statement can be made regarding precision and accuracy. Other techniques which are limited to the number and quantity of contaminants which can be monitored (gas filter correlation or mask filter correlation devices) may have limited applicability in similar applications. However, these types of devices are generally more selective. Backscatter absorption gas imaging (BAGI) may have limited application in identifying the presence of airborne toxic emission sources. However, this method currently cannot yield quantitative data and lacks sufficient sensitivity for certain types of fugitive sources.

In investigations where the source of contamination is unknown, it is desirable to use techniques such as the long path FTIR and UV systems to identify possible contaminants of interest. Depending on site specific factors (i.e., source type, source strength, the presence of background contamination, meteorology, terrain considerations, etc.), these devices may be subject to both chemical and atmospheric interferences which could mask the measurement results. Therefore care must be taken to operate the systems in a manner so as to minimize the effects of atmospheric inferences.

3.3 Perimeter Monitoring Applications

Remote sensing techniques offer a unique means of providing routine continuous surveillance along the perimeter of waste sites under investigation or along the perimeter of petroleum refining and petrochemical manufacturing facilities. These measurements may be useful in detecting emissions of toxic airborne chemicals emanating from stationary point or area sources. The routine surveillance of these chemicals can provide data to assess both community and worker exposure, and in estimating the magnitude of the release of such materials. This type of information is useful in assessing the effectiveness of control devices or the need to assess the effectiveness of routine maintenance procedures aimed at minimizing the fugitive emissions from various types of chemical processes, waste handling facilities, etc. Furthermore, this type of monitoring can be used to warn of the presence of dangerous releases of acutely toxic or flammable gases or vapors.

Perimeter surveillance monitoring is usually performed for a limited number of compounds where the sources are known. For applications such as this, it is vital that the remote sensing device be capable of operating under a variety of conditions (i.e., fog, rain, dust storms, etc.). Furthermore, it is necessary that the device be capable of measuring those constituents of interest both during the day and at night. Thus, active remote sensing techniques are far more suited for this application than passive devices, since these device employ controlled light sources. Differential absorption Lidar (DIAL), long path FTIR, and UV systems offer the greatest potential for conducting these types of measurements.

These types of systems (e.g. DIAL, FTIR, and UV), can be easily adapted for perimeter monitoring applications when operated in the absorption mode. These devices can be used in single ended transmitter/ receiver configuration in combination with strategically placed cornercube retroreflectors. Some systems are configured with a separate transmitter and receiver positioned apart (e.g., double ended design). In either case, these devices can be equipped with rotating optical heads to direct a light beam to a series of reflectance targets (e.g., multiple targeting configuration). This reduces the number of remote sensing detectors required to conduct continuous surveillance along the entire perimeter of a facility or site. In addition, vertical reflector arrays can also be mounted to provide information about plume dispersion characteristics. Micro-computers are used to control the sequencing of the sensor head, and collect, process, and store path averaged concentration measurements for one or more compounds of interest. The remote sensing system can be wired to alarm systems, and the alarms can be triggered when the processed signals from the sensor exceed pre-established path-averaged concentration thresholds.

3.4 Advantages/Disadvantages of Remote Sensing Techniques

There are several obvious advantages to using remote sensing methods over conventional point sampling and measurement techniques to conduct area and perimeter surveillance. Remote sensing can yield a great deal of information over the entire path of interest that could not be obtained otherwise at a reasonable cost using conventional point source sampling and measurement techniques. Furthermore, most remote sensing techniques can provide virtual real-time measurements. This provides rapid feedback of measurements data to allow the investigator to react to changing conditions in the field, while avoiding the lengthy delays encountered by conventional integrated sampling methods that depend on subsequent sophisticated analytical steps. By measuring over longer path distances, it is possible to provide surveillance over larger areas. This feature permits greater temporal and spatial resolution to be obtained.

Path averaged concentration measurements infer that the concentration of the constituents of interest are uniformly distributed over the entire path. Depending on the width of the plume and pathlength over which measurements are made, the concentration of pollutants along a path may not be uniform. Thus, the actual ambient concentrations measured at sensitive receptors downwind of a source may be different. Thus remote sensing results which yield path averaged measurements may not be ideal for estimating dose exposure at discreet locations. Puff releases near the fenceline or other emission "hot spots" may not be identified using remote sensing systems.

Remote sensing methods are generally effective for measuring a variety gases and volatile vapors which have absorption features in the infra-red or ultra-violet spectrum. However, depending on the type of source and emission characteristics, current remote sensing techniques may not possess sufficent senstivity or resolution to identify trace concentrations of constituents of interest in extremely complex matrices. Thus, it may be necessary to augment remote sensing methods with other sampling and analytical techniques to confirm the identity of some gases and vapors.

The support systems for some remote sensing detectors may not be amenable to routine continuous surveillance. Thus, the operational costs may be prohibitive. This is particularly true of those systems which may require liquid cryogens to cool the detector in order to achieve optimum system performance.

Finally, it must be recognized that remote sensing systems are currently not in widespread use. Thus, the capabilities and long term operational effectiveness have yet to be determined. While these systems offer tremendous potential for measuring trace gases from a variety of sources, more effort is required at this time to assess the most suitable application of this technology. As with any application of measurement technology, one must be carefully match the capability with overall program goals. While remote sensing may offer the only practical alternative for some environmental measurement applications, it may not be well suited for others. Therefore, as with any well designed measurement program, the limitations of any measurement methodology must be thoroughly understood and applied correctly to achieve optimum results.

APPENDIX F

PHYSICAL AND CHEMICAL PROPERTY DATA
(From ChemDat 7 Documentation)

The following properties are given for each chemical (listed by name and Chemical Abstract Source [CAS] number):

- Molecular weight
- Density
- Vapor pressure at 25 °C
- Solubility
- Henry's law constant
- Diffusion coefficient in water
- Diffusion coefficient in air
- Boiling point
- Coefficients for the Antoine equation for estimating vapor pressure at temperatures other than 25 °C.

To estimate vapor pressures at temperatures other than 25 °C, the Antoine equation coefficients are used with the following equation:

$$\log_{(10)} \text{Vapor Pressure (mm Hg)} = A - \frac{B}{T + C}$$

where

A, B, and C = the Antoine equation coefficient

T = temperature in °C.

Two approaches may be used to introduce a new compound and its properties into CHEMDAT7. First, the data for one compound in CHEMDAT7 may be replaced with data for the compound of interest in the

- Estimate the biodegradation rate constants using the following methodology:

  -- Approximate K_{max} from available data for K_{max} for compounds of similar structure and/or functional groups; and

  -- Approximate K_1 either by using the following correlation:

$$K_1(L/h/g) = 0.135 \ K_{ow} \ 0.38$$

  where K_{ow} = octanol-water partitioning coefficient

  or by using the default (average) value for K_1, which is $K_1 = 1$ L/h/g, and then calculate K_s as: $K_s = K_{max}/K_1$.

The following properties are given for each chemical (listed by name and Chemical Abstract Source [CAS] number):

- Molecular weight
- Density
- Vapor pressure at 25 °C
- Solubility
- Henry's law constant
- Diffusion coefficient in water
- Diffusion coefficient in air
- Boiling point
- Coefficients for the Antoine equation for estimating vapor pressure at temperatures other than 25 °C.

To estimate vapor pressures at temperatures other than 25 °C, the Antoine equation coefficients are used with the following equation:

$$\log_{(10)} \text{Vapor Pressure (mm Hg)} = A - \frac{B}{T + C}$$

where

A, B, and C = the Antoine equation coefficient

T = temperature in °C.

Two approaches may be used to introduce a new compound and its properties into CHEMDAT7. First, the data for one compound in CHEMDAT7 may be replaced with data for the compound of interest in the columns specified above. With this approach, the list of compounds in CHEMDAT7 remains constant at 62. The second approach involves appending the new compound and its properties to the existing list of chemicals in CHEMDAT7. All the equations/calculations must then be copied from one of the existing rows via Lotus 1,2,3 into the appropriate cells in the new row of the spreadsheet. As mentioned above, the inclusion in CHEMDAT7 of all or a large part of the chemicals listed in this appendix could result in increasing the time required to exercise CHEMDAT7 and could prevent its use on some microcomputers.

The properties of interest listed above, with the exception of the CAS number, mimic those in columns B, D-M, and Q of the CHEMDAT7 spreadsheet.

COMPOUND NAME	CAS #	M.W.	DENSITY (g/cc)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
1,1-CHLOROPHENYLETHANOL	3391-10-4	156.63			2	7.80E-08						
1,1-DIETHYLUREA	634-95-7	116.07			2000	5.80E-08						
1,1-DIPHENYLETHANE	730	182.00			20	9.10E-04						
1,1-DIPHENYLETHANOL	599-67-7	198.14			10000	1.98E-08						
1,2-BENZANTHRACENE	56-55-3	228.29										
1,2-DIBROMO-3-CHLOROPROPANE	96-12-8	236.30			1000	2.30E-05						
1,2-DICHLORO-2-BUTENE	835	124.90			0.02	1.56E+08						
1,3-CYCLOPENTADIENE	722	66.10			2	3.30E-08						
1,3-DIPHENYLBUTADIENE	886-65-7	206.18			10	2.08E-08						
1-BROMO-4-CHLOROCYCLOHEXANE	726	196.50			0.2	9.98E-02						
1-CHLORO-2,2-DIBROMOETHANE		222.5		1	2							
1-CHLORO-2-NITROBENZENE	88-73-3	157.56			2	7.88E-08						
1-METHYL-2-METHOXYAZIRIDINE	474	87.00			20000	4.35E-07						
1-METHYL-3-ACETYLCYCLOPENTADIE253		108.00			2	5.30E-08						
2,2,4-TRIMETHYLPENTANE	540-84-1	114.22		40.6	0.56	1.08E+01						
2,3,5-TRIMETHYL-4-NITROANILINE56		180.00			2	9.00E-08						
2,3,7,8-TETRACHLORODIBENZOFURA808		306.00			2	1.53E-04	0.00E+00	0.00E+00				
2,4,5-TRICHLOROPHENOXYACETIC A93-76-5		255.48		3	10							
2,4,6-TRICHLORO-1,3,5-TRIAZINE108-77-0		184.41			0.2	9.22E-04						
2,4-DIAMINO-6-SULFONYL BENZYL		186		3	25000							
2,4-DIMETHYL-1-NITROBENZENE	25168-04-1	151.16			2	7.58E-08						
2,6 DICHLOROSTYRENE	698	173.00			2	8.80E-08						
2,6-DINITROTOLUENE	606-20-2	182.14			20	9.11E-08						
2-ACETYLFURAN	1192-62-7	110.08			100	1.10E-04						
2-AMINO-3-CHLORO-5-PHENYLCYCLOHEXANONE		193.5		3		0.00000418						
2-AMINO-4-CHLOROPYRIDINE	1072-98-6	128.56		2	10000							
2-AMINO-4-CHLORO-6-CYANOPYRIDI1698		155.00			80	3.10E-04						
2-AMINO-4-NITROBENZYL ALCOHOL	110	162.00			2600	8.08E-08						
2-AMINO-4-NITROTOLUENE	99-55-8	152.17			2	7.61E-08						
2-AMINO-5-CHLOROPYRIDINE	1072-98-6	128.56			50	2.57E-04						
2-BROMO-3-CHLOROBUTADIENE	21	169.00			2	8.46E-08						
2-BROMO-4-CHLORO-6-CYANOBENZYL	112	189.00			1000	1.88E-05						
2-BROMO-4-CYANOMETHYL BENZOATE	59	240.00			0.2	1.20E-01						
2-CHLOROALLYL ALCOHOL	5976-47-6	92.53		1.6	10000	1.83E-05	0.00E+00	0.00E+00	148.0	0	0	0
CHLOROBUTADIENE-1,3	126-99-8	88.50				3.36E-0						

COMPOUND NAME	CAS #	M.W.	DENSITY (g/occ)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
2-CHLOROCYCLOHEXANOL	1561-86-0	134.61			50	2.06E-04						
2-CHLOROETHANOL	107-07-3	80.52		10	100000	1.08E-05						
2-CHLOROPYRIDINE	109-09-1	113.55		1	100	1.49E-08						
2-CHLORO-3-NITRO-5-PHENYLCYCLOHEXANE		180.5		3		4.18E-08						
2-CHLORO-4-AMINOCOUMARAN-6-CARBOXYLIC AC		213.5		3	2000							
2-CHLORO-4-CYANOBENZYL ALCOHOL	115	168.00			2500	6.12E-08						
2-CHLORO-4-METHOXY-6-AMINOBENZ	61	200.00			50	4.00E-04						
2-CHLORO-4-NITROANISOLE		187.5		3	2							
2-CHLORO-4-PHENYLPYRIDINE	405	190.00			2000	9.80E-08						
2-CHLORO-6-AMINO-3-PYRIDINE CA	580	180.00			50	3.08E-04						
2-CYCLOHEXYL-2,2-DIPHENYLETHYL	380	257.00			100	2.57E-04						
2-HYDROXY-6-METHYLPYRIDINE-3-C	38116-61-9	153.14			50	3.08E-04						
2-IODOCOUMARAN		246		3	2							
2-METHYLACETONITRILE	75-86-5	85.12				8.08E-01						
2-METHYLCOUMARAN	607-71-6	140.18			2	8.01E-08						
2-METHYLFURAN	534-22-5	82.11			3000	2.74E-08						
2-METHYLPROPENE	115-11-7	56.00			2	7.00E+00						
2-METHYLTETRAHYDROFURAN	765	86.00			1000	2.17E-02						
2-METHYL-1-PENTENE	763-29-1	84.00			2	1.06E+01						
2-METHYL-4-NITROBENZYL ALCOHOL	20876-18-3	167.16			6000	3.34E-09						
2-NITROPROPANE	79-46-9	89.09			100000	2.23E-04						
2-PROPYN-1-OL	107-19-7	56.06		11.8	100000	8.68E-08						
2-THIOPROPIONAMIDE	91	108.00			3000	5.16E-08						
3,4-BENZOPYRENE	50-32-8	252.32			2	1.28E-04						
3,4-DICHLOROTETRAHYDROFURAN	3511-19-1	141.00			100000	1.41E-07						
3-ACETYLPIPERIDINE	618-42-8	126.00			100000	1.28E-07						
3-ACETYLPYRIDINE	1122-54-9	121.15			100	3.08E-01						
3-ACETYL-5-HYDROXYPIPERIDINE	476	140.00			20000	7.00E-07						
3-AMINOPROPIONITRILE	151-18-8	70.11		2	20000	9.23E-08						
3-BROMOPROPIONITRILE	2417-90-5	133.98	1.615	3	10000							
3-BROMO-4-CYANOMETHYL BENZOATE	636	241.00			1	2.41E-02						
3-CHLORODIMETHYL PHTHALATE	270	229.00			0.2	1.16E-01						
3-CHLOROTETRAHYDROFURAN	604	121.00			100000	3.02E-04						
3-CHLORO-2,5-DIKETOPYRROLIDINE	428	133.50			200000	6.67E-08						
3-CHLORO-4-HYDROXYBIPHENYL	92-04-6	204.66		4	2	5.38E-01						
3-CHLORO-4-METHOXY-5-METHYL-N	[illegible]	[illegible]										

COMPOUND NAME	CAS #	M.W.	DENSITY (g/cc)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
3-CHLORO-4-METHYL-N-METHYLBENZ	480	188.00			2000	9.16E-08						
3-CHLORO-5-CYANOTOLUENE	88	151.00			10	1.51E-08						
3-CHLORO-5-FLUOROTOLUENE	443-83-4	144.52			80	2.88E-04						
3-CYANOPYRIDINE	100-54-9	104.11			100	2.80E-01						
3-HYDROXYPENTANE	737	88.70			56000	4.08E-04						
3-HYDROXY-4-METHYLTETRAHYDROFU	808	108.00			100000	2.58E-04						
3-METHYLCHOLANTHRENE	56-49-5	268.36			2	1.84E-04						
3-NITRO-4-METHYLBENZOATE		195		3	20							
4-ACETYLMETHYLPHTHALATE		238		4	2							
4-AMINO-2-CHLOROTOLUENE	704	140.00			2	7.00E-08						
4-AMINO-4'-CHLOROBIPHENYL		203.5		3	2							
4-BROMOTOLUENE	106-38-7	. 171	1.3950	3	10							
4-CHLOROCYCLOHEXANOL	721	134.6			10	1.86E-08						
4-CHLOROHYDROXYPHENYL METHYL BENZOIC ACI		262.5		3	2000							
4-CHLOROPHTHALIC ANHYDRIDE	554	182.60			5000	3.67E-08						
4-CHLORO-2-METHOXYBENZOIC ACID	67479-70-8	187.00			5	3.74E-08						
4-CHLORO-2-NITROBENZYL ALCOHOL	22996-18-5	187.00			8000	3.74E-08						
4-CHLORO-3-NITROANILINE	635-22-3	172.58			100	1.78E-04						
4-CHLORO-5-CYANOPHTHALIC ACID		225.5		3	1000							
4-CHLORO-5-PHENOXYDIMETHYL PHT	271	320.00			0.2	1.80E-01						
4-CYANOMETHYL BENZOATE	770				2	1.30E-08						
4-CYANOMETHYLPHTHALATE		208		4	2							
4-CYANOTOLUENE	705	117.40			2	1.47E-01						
4-CYCLOHEXYLCYCLOHEXANONE	56025-96-8	80.82			2	4.08E-08						
4-HYDROXYCYCLOHEXANONE		114		3		4.13E-08						
4-HYDROXYDIMETHYL PHTHALATE	272	210.00			0.2	1.05E-01						
4-HYDROXY-5-METHYLDIMETHYL PHT	273	225.00			0.2	1.18E-01						
4-METHYL BENZYL ALCOHOL	709	139.00			1000	1.38E-05						
4-METHYLTHIOPHENOL	106-45-6	124		3		4.40E-07						
4-METHYL-3-NITROBENZYL ALCOHOL	40870-59-5	168.00			2600	6.78E-08						
4-METHYL-5-THIOACETYL-DIHYDRO-1,3-THIAZO		159		3	60							
4-METHYL-TRIHYDRO-1,3-THIAZOLE	484	105.00			100	1.05E-04						
4-NITROSOBENZYL ALCOHOL	701	135.00			1000	1.36E-05						
4-PHENYLCYCLOHEXANONE	4894-75-1	175.00			2	8.76E-08						
4-VINYLCYCLOHEXENE	100-40-3	108.20		25.8	2	1.84E+00						
5,5-DICHLORO-1,3-CYCLOPENTADIE	247	134.60										

COMPOUND NAME	CAS #	M.W.	DENSITY (g/cc)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
5-AMINOMETHYL-3-ISOXAZOLOL	2763-96-4	114.1		0.1	200	7.61E-05						
5-CHLORO-1,3-CYCLOPENTADIENE	346	100.00			0.2	5.00E-02						
5-HYDROXY-1,3-CYCLOPENTADIENE	783	82.00			2	4.06E-08						
5-METHYLFURFURAL	620-02-0	110.11			60000	2.30E-07						
5-METHYL-1,3-CYCLOPENTADIENE	26519-91-5	80.14			0.2	4.08E-02						
ACENAPHTHENE	83-32-9	154.21	1.07	0.005	2	7.71E-08	0.00E+00	0.00E+00	278.0	7.728	2534.234	245.576
ACENAPHTHYLENE	208-96-8	152.21			2	1.14E-04						
ACETALDEHYDE	75-07-0	44.0	0.78	760		9.50E-05	1.41E-05	1.24E-01	20.8	8.005	1600.017	291.809
ACETAMIDE	60-35-5	59.07		1	850000	1.20E-07						
ACETIC ACID	64-19-7	60.05	1.05	15.41		6.27E-02	1.20E-05	1.13E-01	118.0	7.387	1533.313	222.309
ACETIC ANHYDRIDE	108-24-7	102.09	1.04	5.288		5.91E-06	9.33E-06	2.35E-01	139.6	7.149	1444.718	199.817
ACETONE	67-64-1	58.08	0.79	266		2.80E-05	1.14E-05	1.24E-01	56.2	7.117	1210.595	229.664
ACETONE	75-05-8	58.0	0.79	266		2.80E-05	1.14E-05	1.24E-01	56.2	7.117	1210.595	229.664
ACETONITRILE	75-05-8	41.05	0.78	90		5.80E-06	1.66E-05	1.28E-01	81.6	7.119	1314.4	230
ACETOPHENONE	98-86-2	120.16	1.03	1		1.41E-05	0.00E+00	0.00E+00	202.3	9.135	2970.6	273
ACETYL CHLORIDE	75-36-5	78.50	1.11	287.8		0.00E+00	1.15E-05	8.90E-02	52.0	6.948	1115.654	223.554
ACETYL DIETHYLMALONATE	286	194.00			1000	1.94E-05						
ACETYLENE	74-86-2	26.04		40	1085	1.20E-03						
ACROLEIN	107-02-8	56.1	0.84	244.2		5.66E-05	1.22E-05	1.05E-01	53.0	2.387833		
ACRYLAMIDE	79-06-1	71.08	0.00	0.012		5.20E-10	1.06E-05	9.70E-02	87.0	0	0	0
ACRYLIC ACID	79-10-7	72.10	0.00	5.2	5.17E-07	1.00E-07	1.06E-05	9.80E-02	141.6	5.652	648.629	154.683
ACRYLONITRILE	107-13-1	53.1	0.81	114		8.80E-05	1.34E-05	1.22E-01	77.4	7.038	1232.53	222.47
ADAMANTANE DICARBOXYLIC ACID	828-51-3	180.25		4	2							
ADAMANTANE DICHLORIDE	171	207.10			0.2	1.04E-03						
ADIPIC ACID	124-04-9	146.14	1.37	0.0000325		5.08E-11	6.84E-06	6.46E-02	286.0	0	0	0
ALDICARB	116-06-3	190.29			6000	3.17E-08						
ALDRIN	309-00-2	364.90			0.01	3.65E-02						
ALLYL ALCOHOL	107-18-6	58.1	0.85	23.3		1.80E-05	1.14E-05	1.14E-01	97.0	1.357408		
ALLYL CHLORIDE	107-05-1	76.53	0.94	366	100	3.71E-01	0.00E+00	0.00E+00	45.0	0	0	0
ALPHA METHYL STYRENE	98-83-9	118.00	0.00	0.076	2	5.91E-03	1.14E-05	2.64E-01	-30.8	6.923	1486.88	202.40
ALPHA METHYL STYRENE DIMERS	86	236.00			2	1.18E-02						
alpha-CHLORO-beta-METHYLNAPHTH	88-52-2	176.65			2	8.88E-03						
ALPHA-HYDROXYACETALDEHYDE		60		1		9.50E-06						
ALPHA-HYDROXYADIPIMIDE	429	162.00			1000	1.02E-05						
alpha-METHYLSTYRENE (-4)	98-83-9	118.18			2	5.91E-03						
alpha-PICOLINE	1333-41-1	93.14										

COMPOUND NAME	CAS #	M.W.	DENSITY (g/cc)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS		
										A	B	C
AMINOBENZOIC ACID (-p)	150-13-0	137.15			3400	4.08E-08						
AMINOCYCLOHEXANE	108-91-8	99.18			100000	2.40E-04						
AMINOPHENOL(-o)	95-55-6	109.12	0.00	0.511	30000	3.87E-08	8.04E-06	7.74E-02	174.0	0	0	0
AMINOPHENOL(-p)	101-80-4	109.12	0.00	0.888	6500	1.97E-05	2.30E-06	7.74E-02	184.0	-3.357	899.157	-331.343
AMMONIA	7664-41-7	17.03	0.00	7473.255		3.28E-04	6.90E-05	2.59E-01	-33.4	7.55466	1002.711	247.885
AMPHETAMINE	60-15-1	135.23			100	1.26E-04						
AMYL ACETATE(-n)	628-63-7	130.18	0.88	5.422		4.04E-04	1.20E-05	6.40E-02	148.4	0	0	0
ANILINE	62-53-3	93.10	1.02	1		2.60E-06	8.30E-06	7.00E-02	184.0	7.320	1731.515	206.049
ANISOLE	100-66-3	108.13		10	2	7.11E-01						
ANTHRACENE	120-12-7	178.23	1.25	1.30E-06		8.76E-02	0.00E+00	0.00E+00	340.0			
ANTHRAQUINONE	84-65-1	208.20	1.43	3.00E-06		3.30E-09	0.00E+00	0.00E+00	380.0			
AZEPINE	111-49-9	388.30			10000	8.88E-08						
AZIRIDINE	151-56-4	43.10		160	20000	4.54E-04						
BAKELITE	778	100000.00			0.2	5.00E-01						
BENZAL CHLORIDE	98-87-3	161.00	1.26	0.07	2	7.41E-08	0.00E+00	0.00E+00	207.0	0	0	0
BENZALDEHYDE	100-52-7	106.13		1	3300	4.33E-05						
BENZALKONIUM CHLORIDE	180	182.00			10000	1.60E-06						
BENZENE	707	78.1	0.87	95.2		5.50E-03	9.80E-06	8.80E-02	80.1	6.905	1211.033	220.79
BENZENE SULFONIC ACID	707	158.17			30000	7.81E-07						
BENZETHONIUM CHLORIDE	121-54-0	448.15			3000	2.34E-05						
BENZODIOXANE-1,3	151	238.30			8000	4.07E-08						
BENZOIC ACID	65-85-0	122.13	1.27	0.00704		1.52E-08	7.97E-06	0.00E+00	249.2	9.033	3333.3	273
BENZONITRILE	100-47-0	103.07		1	10000	1.38E-05						
BENZOPHENONE	119-61-9	182.23			2	8.11E-08						
BENZOTHIAZOLE	95-16-9	135.19			100	1.30E-04						
BENZOTRICHLORIDE	98-07-7	195.47	1.38	0.2		2.16E-03	0.00E+00	0.00E+00	221.0	0	0	0
BENZOYL CHLORIDE	98-88-4	140.57		214		0.00E+00						
BENZO(A)ANTHRACENE	56-55-3	228.30	1.11	1.5E-07		1.26E-08	9.00E-06	5.10E-02	58.9	0	0	0
BENZO(A)PYRENE	50-32-8	252.30	1.11	5.60E-04		1.38E-09	9.00E-06	4.30E-02	312.0	0	0	0
BENZO(B)FLUORANTHENE	205-99-2	252.32	0.00	1026		2.06E-05	0.00E+00	0.00E+00	4.0	0	0	0
→ BENZYL ALCOHOL 116.62	100-51-6	108.15	1.0419	0.15	35000	8.10E-07				0	0	0
BENZYL CHLORIDE	100-44-7	126.6	1.10	1.21		4.38E-04	7.80E-06	7.50E-02	179.4	0.082788		
BENZYL METHYL ETHER	538-86-3	122.16	0.987	3	10							
beta-PROPIOLACTONE	57-57-8	72.10		3.4	360000	9.22E-07						
BICYCLO[2.2.1]-2,5-HEPTADIENE	172	158.00			0.2	7.90E-02						

COMPOUND NAME	CAS #	M.W.	DENSITY (g/cc)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
BISPHENOL (A)	80-05-7	228.31			10	2.28E-08						
BIS(1,1,2,2-TETRACHLOROPROPYL)	160	377.70		874.7	10	4.38E+01			21.3			
BIS(2-CHLOROETHYL)ETHER	111-44-4	143.00	1.22	1.4		1.30E-05	7.53E-06	6.92E-02	178.0	0	0	0
BIS(2-CHLOROISOPROPYL)ETHER	108-60-1	171.10	1.11	0.85		1.10E-04	6.41E-06	6.02E-02	189.0	0	0	0
BIS(2-ETHYLHEXYL)PHTHALATE	117-81-7	388.07	0.00	2.0E-07		3.00E-07	3.66E-06	3.51E-02	384.0	0	0	0
BIS(CHLOROMETHYL)ETHER	542-88-1	115.00	1.32	30		2.10E-04	9.38E-06	8.36E-01	104.0	0	0	0
BROMOBENZENE	108-86-1	157.02	1.4952	3	400							
BROMOBENZYL ALCOHOL -(m)	15852-73-0	187.04			6000	3.74E-08						
BROMOBENZYL ALCOHOL -(o)	18982-54-2	187.04			6000	3.74E-08						
BROMOBENZYL ALCOHOL -(p)	873-75-6	187.04			6000	3.74E-08						
BROMOCHLOROBENZYL ALCOHOL	114	205.00			2500	8.30E-08						
BROMOCHLOROMETHANE	74-97-5	129.39			10	2.86E+01						
BROMOCHLOROMETHYL ACETATE	388	187.00			100000	1.87E-07						
BROMODICHLOROMETHANE	75-27-4	163.80	1.97	50.15	200	2.05E-01	0.00E+00	0.00E+00	90.0	0	0	0
BROMOETHYL ACETATE	927-68-4	167.02			100000	4.18E-04						
BROMOETHYLENE	593-60-2	106.96			2	1.34E+01						
BROMOFORM	75-25-2	252.77	2.89	5.6	3100	5.84E-04	0.00E+00	0.00E+00	149.5	0	0	0
BROMOMETHANE	74-83-9	94.95	0.00	1501.80	900	2.21E-01	0.00E+00	0.00E+00	4.6	0	0	0
BROMO-(1)-CHLOROETHANE-2	107-04-0	143.42			0.2	1.79E+02						
BUTADIENE-(1,3)	106-99-0	54.09	0.00	2095.046		1.42E-01	1.08E-05	2.49E-01	-4.4	6.849	930.546	238.854
BUTANE	106-97-8	58.12			400	2.81E-01						
BUTANOL (S)	78-92-2	74.14		10	77000	1.27E-05						
BUTANOL-1	71-36-3	74.1	0.81	6.5		8.90E-06	9.30E-06	8.00E-02	117.7	7.476	1362.39	178.77
BUTYL ACETATE(-n)	123-86-4	116.00	0.88	15	14000	1.04E-04	0.00E+00	0.00E+00	126.0	7.127	1430.418	210.745
BUTYL ACRYLATE	141-32-2	128.20	0.90	5.9	1600	6.11E-04	0.00E+00	0.00E+00	145.0	0	0	0
BUTYL BENZENE	104-51-8	134.22		1	2	8.08E-02						
BUTYL BENZYL PHTHALATE	85-68-7	312.39			2.9	1.08E-02						
BUTYL CARBITOL	112-34-5	162.23	0.98	4.00E-06	0.2	8.11E-02	0.00E+00	0.00E+00	231.0	0	0	0
BUTYL CELLOSOLVE	111-76-2	118.20	0.90	1.01	45000	2.08E-07	0.00E+00	0.00E+00	170.0	8.958	1399.908	172.154
BUTYL MERCAPTAN	881	90.18			100	2.25E-01						
BUTYLENE GLYCOL-(1,3)	107-88-0	90.14		0.06	2000	3.80E-08						
BUTYRALDEHYDE	123-72-8	72.11			70000	2.68E-04						
BUTYRIC ACID	107-92-6	88.10		0.84	58200	1.78E-08						
CAMPHENE	79-92-5	136.23	0.84		10	1.38E-08	0.00E+00	0.00E+00	159.0	0	0	0
CARBAZOLE	86-74-8	167.20		1	2	4.40E+01						

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CARBON TETRACHLORIDE	56-23-5	153.8	1.59	113		3.00E-02	8.80E-06	7.80E-02	76.8	6.9339	1242.43	230
CELLULOSE	9000-11-7	504.27		0	10	5.94E-05	0.00E+00	0.00E+00				
CHLORAL	302-17-0	147.40	1.51	50	10000	9.70E-04	0.00E+00	0.00E+00	97.8	0	0	0
CHLORDANE	57-74-9	410.00	1.11	1.0E-05		9.67E-05	0.00E+00	0.00E+00	0.0	0	0	0
CHLORINATED TARS	885	800.00				1.76E-04						
CHLOROACETALDEHYDE	107-20-0	78.50	1.11	80		2.40E-05	1.15E-05	9.90E-02	85.0	0	0	0.
CHLOROACETIC ACID	79-11-8	94.50		1	850000	1.11E-08						
CHLOROANILINE(2)	95-51-2	127.60		1	10	1.08E-02						
CHLOROANILINE(3)	108-42-9	127.57		1	10	1.08E-02						
CHLOROAZOBENZENE	128	216.70			2	1.08E-02						
CHLOROBENZENE	108-90-7	112.6	1.11	11.8		3.98E-03	8.70E-06	7.30E-02	132.0	6.978	1431.05	217.55
CHLOROBENZENESULFONIC ACID (-p	100-03-8	178.62			2000	8.83E-08						
CHLOROBENZOIC ACID (-o)	118-91-2	156.57			2100	7.40E-08						
CHLOROBENZOPHENONE (PARA)	134-85-0	216.67		2.80E-06		3.40E-09			330.0			
CHLOROBENZYL ALCOHOL -(m)	873-63-2	142.59			6000	2.86E-08						
CHLOROBENZYL ALCOHOL -(o)	17849-38-6	142.59			6000	2.86E-08						
CHLOROBENZYL ALCOHOL -(p)	873-76-7	142.59			6000	2.86E-08						
CHLOROBIPHENYL (-p)	180	188.00			2	8.40E-08						
CHLOROCYANOBENZENE (1,4)	873-32-5	137.60			2	1.72E+01						
CHLOROCYCLOHEXANE	542-18-7	118.61			2	1.48E+01						
CHLORODIACETYL		120.5		2								
CHLOROETHANE	75-00-3	64.52		1000	5740	1.48E-02						
CHLOROETHYL(2-) VINYL ETHER	110-75-8	106.55		24.7	100	3.48E-02			109.0			
CHLOROFLUOROMETHANE	593-70-4	68.48			10	1.71E+00						
CHLOROFORM	67-66-3	119.4	1.49	208		3.39E-03	1.00E-05	1.04E-01	61.2	6.493	929.44	196.03
CHLOROMETHANE	74-87-3	50.49		3800	6000	8.14E-03						
CHLOROMETHYL ACETYLENE		74.5		2	10							
CHLOROMETHYL ETHYL KETONE	280	106.55			10000	2.08E-08						
CHLOROMETHYL PHENYL KETONE	532-27-4	154.60			6000	3.09E-08						
CHLOROMETHYLAMIDOIMINE		78.5		3	2000							
CHLORONAPTHALENE-2	91-58-7	162.61		0.017	0.2	1.82E-02	0.00E+00	0.00E+00	256.0			
CHLORONITROALKOXYIMINE	430	280.00			1000	2.30E-05						
CHLORONITROBENZENE(-o)	88-73-3	157.56			2	7.86E-08						
CHLOROPHENOL POLYMERS	888	2000.00			20000	1.00E-07						
CHLOROPHENOL-2	95-57-8	128.60	1.26	3	28500	1.78E-05	0.00E+00	0.00E+00	175.8	6.877	[illegible]	

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CHLOROPHENOL-4	106-48-9	128.60	1.31	0.18	27100	1.12E-06	0.00E+00	0.00E+00	217.0	0	0	0
CHLOROPRENE	126-99-8	88.5	0.958	273		3.36E-01	1.00E-05	1.04E-01	59.4	6.161	783.45	179.7
CHLOROPROPANE-1	540-54-5	78.54	0.89	350		1.30E-02			47.2			
CHLOROPROPANE-2	75-29-6	78.54	0.87	523		1.70E-02			35.5			
CHLOROPROPYLENE-2	557-98-2	76.53				3.60E-01						
CHLOROSTYRENE (-4)	1331-28-8	138.60			2	6.09E-03						
CHLOROTOLUENE-4	106-43-4	126.60	1.07	2.6	100	4.00E-03			162.0			
CHLORO(-3)PROPENE-1	557-98-2	76.60		361	100	3.60E-01						
CHLORO(-p)CRESOL(-m)	59-50-7	142.60	0.00	3.50E-03	4000	1.04E-07	0.00E+00	0.00E+00	235.0	0	0	0
CHLORO(-p)PHENYLHYDRAZINE	541	142.00			80	2.04E-04						
CHLORO-1,2-ETHANE DIOL	402	96.52			100000	9.65E-08						
CHLORO-p-XYLENE	104-82-5	140.61		60	0.2	5.85E+01						
CHRYSENE	218-01-9	228.30	1.11	5.70E-10		1.18E-06	0.00E+00	0.00E+00	448.0	0	0	0
CITRIC ACID	77-92-9	192.12	1.665	0.001	400000	8.33E-10						
COPPER PHTHALOCYANINE	147-14-8	576.10			10	5.70E-03						
COUMARAN	91-64-5	146.15		1	2	9.83E-02						
CREOSOTE	8001-58-9	400.00			5000	8.00E-03						
CRESOL	1319-77-3	108.00		0.3	2000	2.18E-05						
CRESOL(-m)	108-39-4	108.1	1.03	0.08		4.40E-07	1.00E-05	7.40E-02	202.0	7.508	1856.36	199.07
CRESOL(-o)	95-48-7	108.1	1.05	0.24		2.60E-06	8.30E-06	7.40E-02	190.8	6.911	1435.5	165.16
CRESOL(-p)	106-44-5	108.1	1.03	0.11		4.43E-07	1.00E-05	7.40E-02	202.0	7.035	1511.08	161.85
CRESYLIC ACID		108.0	1.05	0.3		1.70E-03	8.30E-06	7.40E-02	235.0	-0.52280		
CROTONALDEHYDE	470-30-3	70.09	0.85	30		1.54E-05	1.00E-05	9.02E-02	89.0	0	0	0
CROTONYLENE	503-17-3	54.09			2	8.70E+00						
CUMENE (Isopropylbenzene)	98-82-8	120.2	0.86	4.6		1.46E-02	7.10E-06	6.50E-02	153.0	6.963	1460.793	207.78
CUMYLPHENOL-4	27576-86-9	212.29	0.00	0.000032	2	1.68E-06	0.00E+00	0.00E+00	335.0	0	0	0
CYANIDE	57-12-5	27.00	0.00	0	100000	2.70E-03	0.00E+00	0.00E+00	0.0	0	0	0
CYANOGEN	460-19-5	52.04	0.95	3980		4.90E-03			-21.2			
CYANOGUANIDINE	461-58-5	84.08		3	10000							
CYANOPYRIDINE (-4)	100-48-1	104.11	0.00	0	100	2.60E-01	8.77E-06	7.99E-02	0.0	0	0	0
CYANURIC ACID	108-80-5	129.09			5000	2.99E-03						
CYCLOHEXANE	110-82-7	84.20	0.78	100		1.37E-02	9.10E-06	8.39E-02	81.0	6.841	1201.53	222.65
CYCLOHEXANOL	108-93-0	100.20	0.95	1.22		4.47E-06	8.31E-06	2.14E-01	161.0	6.255	912.87	109.13
CYCLOHEXANONE	108-94-1	98.2	0.95	4.8		4.13E-06	8.62E-06	7.84E-02	167.0	0.681268		
CYCLOHEXENE	110-83-8	82.15				1.08E+01						
CYCLOHEXYL ACETATE	622-45-7	142.22										

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CYCLOPENTADIENE	203	66.10	0.82	4	2	1.90E+01	0.00E+00	0.00E+00	40.0			
DACRON	888	100000.00			0.2	5.00E-01						
DDT	50-29-3	354.49			0.0031	1.14E-01						
DIACETYL	431-03-8	86.10			250000	6.61E-05						
DIBENZO(A,H)ANTHRACENE	53-70-3	278.36		5.200E-11		3.01E-08						
DIBROMOCHLOROMETHANE	124-48-1	208.29	2.38		0.2	2.08E+03	0.00E+00	0.00E+00	122.0	0	0	0
DIBROMOETHANE-1,2	106-93-4	187.88			4310	1.09E-02						
DIBROMOMETHANE	74-95-3	173.85		48	11000	9.99E-04						
DIBUTYL ETHER	142-96-1	130.22	0.87	7	300	4.00E-03						
DIBUTYLPHTHALATE	84-74-2	278.30	1.47	0.00001		2.80E-07	7.86E-06	4.38E-02	340.0	6.639	1744.20	113.59
DICHLOROBENZENE(1,2) (-o)	95-50-1	147.0	1.31	1.5		1.94E-03	7.90E-06	6.90E-02	179.0	0.178097		
DICHLOROBENZENE(1,3) (-m)	541-73-1	147.01	1.29	2.28		3.61E-03	7.86E-06	6.92E-02	172.0	0	0	0
DICHLOROBENZENE(1,4) (-p)	106-46-7	147.0	1.29	1.2		1.60E-03	7.90E-06	6.90E-02	173.4	0.079184		
DICHLOROBIPHENYL (PARA)	213089-08-	223.10	0.00	0	0.62	3.60E-02	5.84E-06	5.28E-02	0.0	0	0	0
DICHLOROBUTANE (1,4)	110-56-5	127.01			10	3.18E+00						
DICHLORODIFLUOROMETHANE	75-71-8	120.92	0.00	5000		4.01E-01	0.00E+00	0.00E+00	-29.8	0	0	0
DICHLORODIPHENYLMETHANE	2051-90-3	237.00			2	1.10E-02						
DICHLOROETHANE(1,1)	75-34-3	99.00	1.17	234	5500	5.54E-03	0.00E+00	0.00E+00	57.0	0	0	0
DICHLOROETHANE(1,2)	107-06-2	99.0	1.26	80		1.20E-03	9.90E-06	1.04E-01	83.4	7.025	1272.3	222.9
DICHLOROETHYLENE(1,1)	75-35-4	97.00	1.21	630.1		1.80E-02			-99.8			
DICHLOROETHYLENE(1,2)	156-54-2	96.95	1.28	200	800	3.19E-02	0.00E+00	0.00E+00	60.0	6.965	1141.9	231.9
DICHLOROMETHANE	75-09-2	84.94		400	20000	2.34E-03						
DICHLOROMONOFLUOROMETHANE	75-43-4	102.92		1380	0.2	9.21E+02	0.00E+00	0.00E+00	9.0			
DICHLOROPHENOL(2,4)	120-83-2	163.01		0.1		4.80E-06	0.00E+00	0.00E+00	210.0			
DICHLOROPHENOL(2,6)	87-65-0	163.00		0.084		4.80E-06	0.00E+00	0.00E+00	220.0	0	0	0
DICHLOROPHENOXYACETIC ACID(2,4	94-75-7	221.00	0.00	290.5	890	6.21E-02	6.46E-06	5.98E-02	47.2	0	0	0
DICHLOROPROPANE(1,2)	78-87-5	113.0	1.16	40		2.30E-03	8.73E-06	7.82E-02	96.8	6.98	1380.1	22.8
DICHLOROPROPENE(1,3)	542-75-6	111.00	1.20	43	2700	2.38E-03	0.00E+00	0.00E+00	112.0	0	0	0
DICHLOROPROPYLENE-2,3	78-88-6	110.97			2150	1.29E-02						
DICHLORO(1,3)PROPANOL(-2)	96-23-1	129.00	1.35	0.27	100000	4.80E-04	0.00E+00	0.00E+00	82.0	0	0	0
DICHLORO(2,3)PROPANOL(-1)	616-23-9	129.00	1.36	7		2.34E-05	0.00E+00	0.00E+00	182.0	0	0	0
DICHLORO-2-BUTENE(1,4)	764-41-0	125.00	1.19	2.87		2.66E-04	8.12E-06	7.26E-02	158.0	0	0	0
DICHLORO-TRANS-ETHYLENE(1,2)	540-59-0	96.94		400	600	6.60E-03						
DICHLORO-(2,6)-NITROANILINE(4)	99-30-9	206.99		0.0000012	50	6.54E-09						
IETHYL AMINE	109-89-7	73.14			20000	7.31E-08						

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DIETHYL ETHER ACID CHLORIDE		136.6		3	100							
DIETHYL PHTHALATE	84-66-2	222.00	1.12		2	1.11E-02						
DIETHYL THIOETHER	352-93-2	90.00			80	4.80E-01						
DIETHYL (N,N) ANILINE	91-66-7	149.23	0.93	0.002826	14400	5.74E-08	5.87E-06	5.12E-02	298.0	0	0	0
DIETHYLENE GLYCOL	111-46-6	106.14		1	100000	1.40E-08						
DIHYDRO-5-OXAZALONE (DIHYDROAZLACTONE)		101		3	5000							
DIISOPROPYL BENZENE (PARA)	100-18-5	162.28		1	2	1.07E-[illegible]						
DIMETHOATE	60-51-5	229.27			25000	9.17E-[illegible]						
DIMETHOXY METHANE	109-87-5	76.10		400	330000	1.21E-04						
DIMETHOXY-(3,3')-BENZIDINE	119-90-4	244.32			10	2.44E-08						
DIMETHYL AMINE	124-40-3	45.08		1520		5.24E-08						
DIMETHYL DISULFIDE	624-92-0	94.20			6300	1.60E-03						
DIMETHYL FORMAMIDE	68-12-2	73.09	0.95	3.696	20000	1.92E-05	1.03E-05	9.39E-02	152.8	6.928	1400.87	196.43
DIMETHYL HYDRAZINE(1,1)	57-14-7	60.10	0.80	157	100000	1.24E-04	1.06E-05	1.06E-01	63.0	7.408	1305.91	225.53
DIMETHYL NITROSAMINE		74.08	1.005				1.00E-05	1.04E-01	153			
DIMETHYL PHTHALATE	131-11-3	194.20	1.19	0.000187		2.15E-08	6.29E-06	5.68E-02	283.8	4.522	700.31	51.42
DIMETHYL SULFATE	77-78-1	126.14		0.1		5.88E-07						
DIMETHYL SULFIDE	75-18-3	62.13		420	6300	5.46E-03						
DIMETHYLBENZYL HYDROPEROXIDE	80-15-9	152.21		0.24	100	4.81E-04						
DIMETHYLBENZ(A)ANTHRACENE(7,1	257-97-6	256.33	0.00	0.00000000	2	2.78E-10	4.98E-06	4.81E-02	477.0	0	0	0
DIMETHYLETHYLAMINE	75-64-9	73.10	1.11	30	5000	3.86E-04						
DIMETHYLPHENOL(2,4)	105-67-9	122.16	1.04	0.0678	10	9.21E-04	0.00E+00	0.00E+00	211.5	0	0	0
DINITROBENZENE(-m)	99-65-0	168.10	1.58	0.05		2.20E-05	7.64E-06	2.78E-01	300.0	4.337	229.2	-137
DINITROPHENOL(2,4)	51-28-5	184.00	1.68	59.8		1.58E-07	0.00E+00	0.00E+00	83.9	0	0	0
DINITROTOLUENE(2,4)	121-14-2	182.10	1.31	0.0051		4.07E-06	7.06E-06	2.08E-01	300.0	5.798	1118	61.8
DINITRO-o-CRESOL(4,6)	534-52-1	198.00		0.018		1.40E-05	0.00E+00	0.00E+00	264.7			
DINOCAP	39300-45-3	364.40		.001	2	1.90E+05			-168.7			
DIOXANE(1,4)	123-91-1	88.20	1.03	37		2.31E-05	1.02E-05	2.29E-01	101.0	7.431	1554.68	240.34
DIOXIN	828-00-2	322.0	1.83	1.52E-09	3.000E-11	8.12E-05	5.60E-06	1.04E-01	421.4	12.88	6465.5	273
DIPHENYL ETHER	101-84-8	170.21	1.075	0.02	2	2.24E-08						
DIPHENYL THIOETHER	139-66-2	186.28			2	9.31E-08						
DIPHENYLAMINE	122-39-4	169.20	1.16	0.00376		2.78E-08	6.31E-06	5.80E-02	302.0	0	0	0
DIPHENYLCHLOROMETHANE	90-99-3	202.00			2	1.01E-02						
DIPHENYLDIKETONE	134-81-6	210.24			2	1.05E-02						
DIPHENYLHYDRAZINE(1,2)	122-66-7	184.23		0.0000523		1.00E-10	0.00E+00	0.00E+00	[illegible]			

COMPOUND NAME	CAS #	M.W.	DENSITY (g/cc)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
DIPROPYLAMINE	142-84-7	101.22			100000	2.60E-04						
DIVINYL KETONE	24	70.00			40000	4.30E-04						
DI-n-OCTYL PHTHALATE	117-84-0	390.62			0.285	1.37E-01						
EPICHLOROHYDRIN	106-89-8	92.5	1.18	17		3.23E-05	9.80E-06	8.60E-02	117.0	1.230494		
EPINEPHRINE	51-43-4	183.21			500	3.08E-07						
ETHANOL	64-17-5	46.10	0.79	50	100000	3.03E-06	1.30E-05	1.23E-01	78.4	8.321	1718.21	237.52
ETHANOLAMINE(mono-)	141-43-5	61.08	1.02	0.4	100000	3.23E-07	1.14E-05	1.07E-01	172.0	7.456	1577.67	173.37
ETHOXYETHANOL-2	110-80-5	90.00	0.93	5.4	100000	6.30E-08	0.00E+00	0.00E+00	135.0	7.874	1843.5	234.2
ETHYL ACETATE	141-78-6	88.10		100		1.28E-04						
ETHYL ACETATE PEROXIDE	382	120.00			10000	3.00E-08						
ETHYL ACRYLATE	140-88-5	100.00	0.92	40		3.50E-04	8.60E-06	7.70E-02	100.0	0	0	0
ETHYL BENZENE	100-41-4	106.16	0.86	10		6.44E-03	7.80E-06	7.50E-02	136.2	6.975	1424.255	213.21
ETHYL CHLORIDE	75-00-3	64.52	0.90	1200		6.10E-03	1.15E-05	2.71E-01	12.4	6.986	1030.01	238.61
ETHYL CYANIDE	107-12-0	55.08		40	80000	2.76E-04						
ETHYL ETHER	60-29-7	74.12	0.71	520		6.80E-04	9.30E-06	7.40E-02	34.5	6.920	1064.07	228.8
ETHYL ISOPROPYL PEROXIDE	388	104.00			100000	2.60E-04						
ETHYLACETATE		88.1	0.90	100		1.28E-04	9.66E-06	7.32E-02	77.0	7.101	1244.95	217.88
ETHYLBENZENE		106.2	0.87	10		6.44E-03	7.80E-06	7.80E-02	136.2	6.975	1424.255	213.21
ETHYLENE	74-85-1	28.05			131	4.40E-01						
ETHYLENE CHLOROHYDRIN	107-07-3	80.52		10	100000	1.08E-05						
ETHYLENE DIAMINE	107-15-3	60.11		10.7	100000	8.40E-09						
ETHYLENE DIBROMIDE	106-93-4	187.88	2.70	14		6.30E-04	0.00E+00	0.00E+00	131.6	6.721	1280.82	201.75
ETHYLENE DICHLORIDE	107-06-2	98.96	1.25	82		1.20E-03	9.90E-06	1.04E-01	83.5	7.025	1272.3	222.9
ETHYLENE GLYCOL	107-21-1	62.07	1.11	0.1250	100000	1.08E-07	1.22E-05	1.08E-01	198.0	8.090	2088.9	203.5
ETHYLENE GLYCOL DIMETHYL ETHER	110-71-4	90.12		48	100000	6.09E-05						
ETHYLENE GLYCOL MONOMETHYL ETH	109-86-4	76.10		0.78	100000	7.01E-07						
ETHYLENE GLYCOL MONOMETHYL ETH	110-49-6	118.15		2	100000	3.11E-06						
ETHYLENE OXIDE	75-21-8	44.0	0.87	1250		1.42E-04	1.45E-05	1.04E-01	10.7	7.128	1054.54	237.76
ETHYLETHER		74.1	0.71	520		6.80E-04	9.30E-06	7.40E-02	34.5	6.92	1064.07	228.8
ETHYL(2) HEXANOL	104-76-7	130.22		0.36	1000	6.17E-05						
ETHYL-(2)-PROPYL-(3) ACROLEIN	645-62-5	92.50	1.18	17		3.23E-05	9.80E-06	8.60E-02	117.0	0	0	0
FLUORANTHENE	206-44-0	202.00	0.00	0.0177	0.3	6.73E-03	0.00E+00	0.00E+00	260.0	6.373	1756	118
FLUORENE	86-73-7	166.00	1.20	0.0000183	2	1.70E-03	0.00E+00	0.00E+00	293.0	7.701	2037.1	243.2
FLUOROACETIC ACID, SODIUM SALT	62-74-8	100.02			20000	5.00E-09						
FORMALDEHYDE	50-00-0	30.0	0.									

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FREONS		120.92	1.486	5000		4.01E-01	1.00E-05	1.04E-01	-29.8	3.080108		
FUMARIC ACID	110-17-8	116.07			7000	1.09E-08						
FURAN	110-00-9	68.08	0.94	596.207		5.34E-03	1.22E-05	1.04E-01	31.4	6.975	1060.87	227.74
FURFURAL	98-01-1	96.09	1.16	2		8.11E-05	1.04E-05	8.72E-02	161.7	6.575	1198.7	162.8
FUROIC ACID	88-14-2	112.08		2	38000							
GLUTARIC ACID	110-94-1	132.11			640000	2.08E-08						
GLYCERIN	56-81-5	92.09	1.26	0.00016		1.30E-08	0.00E+00	0.00E+00	291.0			
GLYCEROL	56-81-5	92.10		0.00016	10000	1.94E-08						
GLYCINAMIDE	598-41-4	74.10			80000	1.40E-07						
GUANIDINE, NITROSO	674-81-7	88.08			10000	8.81E-07						
GLYCIDOL	556-52-5	74.08	1.11	0.905	100000	9.08E-07	0.00E+00	0.00E+00	162.0			
HEPTACHLOR	76-44-8	373.35	1.57	0.0003		2.30E-03	0.00E+00	0.00E+00	10.2	0	0	0
HEPTANE(-n)	142-82-5	100.02	0.68	46	3	2.03E+00	0.00E+00	0.00E+00	98.4	6.898	1264.9	216.54
HEXACHLOROBENZENE	118-74-1	284.80	2.04	1		6.80E-04	5.91E-06	5.42E-02	322.0	0	0	0
HEXACHLOROBUTADIENE	87-68-3	260.8	1.67	0.15		2.88E-02	6.16E-06	5.61E-02	215.0	-0.82308		
HEXACHLOROCYCLOHEXANE (GAMMA	58-89-9	290.88	1.87	0.0000094	17	7.80E-06						
HEXACHLOROCYCLOPENTADIENE	77-47-4	272.8	1.71	0.081		1.60E-02	6.16E-06	5.61E-02	234.0	-1.09155		
HEXACHLOROETHANE	67-72-1	237.00	2.09	0.65		2.49E-03	6.80E-06	2.49E-03	186.0	0	0	0
HEXACHLOROPENTADIENE	416	276.00			2	1.38E-02						
HEXANE(-n)	110-54-3	86.20	0.66	150.3		1.22E-01	7.77E-06	2.00E-01	69.0	6.876	1171.17	224.41
HEXANOIC ACID	142-62-1	116.08			11000	1.08E-08						
HEXANOL-1	111-27-3	102.18	0.82	0.8115		1.88E-05	7.53E-06	6.90E-02	158.0	7.860	1761.26	196.66
HHB	surrogate	98.4		1		5.38E-08	9.40E-06	8.73E-02				
HLB	surrogate	144.0		1		3.00E-02	9.86E-06	8.76E-02				
HAB	surrogate	117		1		1.18E-08	8.24E-06	7.40E-02				
HYDRAZINE	302-01-2	32.06		14.4		8.69E-07						
HYDROCYANIC ACID	74-90-8	27.00	0.69	726		4.65E-07	1.82E-05	1.97E-01	25.7	7.528	1329.5	260.4
HYDROFLUORIC ACID	7664-39-3	20.00	0.00	900	100000	2.37E-04	3.30E-05	3.88E-01	19.7	7.217	1268.37	273.87
HYDROGEN SULFIDE	7783-06-4	34.10	0.00	15200		2.30E-02	1.61E-05	1.76E-01	-60.2	7.614	885.319	250.25
HYDROQUINONE	123-31-9	110.12			70000	1.57E-07						
HYDROXY DIMETHYL ETHER	276	78.00			1000	1.96E-02						
HYDROXYACETIC ACID	79-14-1	76.05			100000	1.80E-04						
HYDROXYMETHYL ACETYLENE		56		2	10							
HYDROXYMETHYL ISOPROPYL KETONE	281	90.00			10000	2.26E-08						
HYDROXYMETHYL THIOBENZENE	63	140.00			2	7.00E-08						

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HYDROXY-(2)-PROPIONITRILE	109-78-4	71.08		0.08	100000	7.46E-08						
INDENO(1,2,3-cd)-PYRENE	193-39-5	276.34		0.00000000		6.07E-13	0.00E+00	0.00E+00	536.0			
ISOBUTYL ALCOHOL (ISOBUTANOL)	78-83-1	74.0	0.79	10		2.20E-08	9.30E-06	8.60E-02	107.9	1.000088		
ISOBUTYRALDEHYDE	78-84-2	72.12		170	110000	1.47E-04						
ISOHEPTANE	31394-54-4	100.21	0.00	65.97	2	4.28E+00	7.11E-06	1.87E-01	0.0	0	0	0
ISOPHORONE	78-59-1	138.21	0.92	0.438		5.78E-06	6.76E-06	6.23E-02	215.0	0	0	0
ISOPROPANOL	67-63-0	60.09	0.79	42.8	100000	1.60E-04	1.04E-05	9.80E-02	82.4	8.117	1580.92	219.61
ISOPROPYL ACETATE	108-21-4	102.13		73	30900	3.17E-04						
ISOPROPYL ETHER	108-20-3	102.18		150	9000	2.24E-03						
ISOPROPYLAMINE	75-31-0	59.08		460	100000	3.60E-04						
LEAD ACETATE	301-04-2	325.28				7.24E-10						
LEAD SUBACETATE	1335-32-6	807.69				1.47E-08						
LEUCINE	61-90-5	131.20			24300	5.40E-07						
LIND	surrogate	97.3		1		1.68E-07	9.04E-06	8.27E-02		0		
LIND	surrogate	78.4		1		1.68E-07	1.18E-05	1.00E-01		0		
MALEIC ACID	110-16-7	116.07			788000	1.47E-08						
MALEIC ANHYDRIDE	108-31-6	98.1	0.98	0.0001	700	4.00E-08	1.11E-05	9.80E-02	200.0	-4.00014		
MELAMINE	108-78-1	126.20		50	100	8.20E-02						
MERCURY	7439-97-6	200.59		0.002		1.14E-02						
MESITYL OXIDE	141-79-7	98.15			28000	3.51E-07						
METHACRYLIC ACID	79-41-4	86.10		0.1	1000	1.18E-05						
METHANE	74-82-8	16.04			24	1.34E+00						
METHANE SULFONIC ACID	75-75-2	96.11			20000	4.81E-07						
METHANETHIOL	74-93-1	48.11		1520	23000	4.16E-03						
METHANOL	67-56-1	32.0	0.79	114		2.70E-06	1.64E-05	1.50E-01	65.0	7.897	1474.08	229.13
METHOMYL	16752-77-5	162.20			30000	8.11E-07						
METHOXYACETIC ACID	275	90.00			8000	1.80E-08						
METHOXYACETONITRILE	1738-36-9	71.04			100000	1.78E-04						
METHYL 1-[(BUTYLAMINO) CARBONY	182	290.00			2	1.26E-02						
METHYL ACETATE	79-20-9	74.1	0.92	235	3000	1.02E-04	1.00E-05	1.04E-01	54.0	7.065	1157.63	219.73
METHYL ACRYLATE	96-33-3	86.10			60000	1.44E-07						
METHYL CHLORIDE	74-87-3	50.50	0.95	3830	8000	8.14E-03	6.50E-06	1.26E-01	-24.0	7.093	948.58	249.34
METHYL CHLOROCARBONATE	79-22-1	94.50			100	2.36E-02						
METHYL CYCLOHEXANE	108-87-2	242.32		43	14	9.76E-01						
METHYL ETHER	115-10-6	46.08		3982	76000	3.18E-03						
METHYL ETHYL KETONE	78-93-3	72.1	0.82	100		[illegible]						

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METHYL FORMATE	107-31-3	60.05		600	304	1.30E-01						
METHYL HYDRAZINE	60-34-4	46.09		49.6		3.44E-08						
METHYL IODIDE	74-88-4	141.94			14000	2.52E-03						
METHYL ISOAMYL KETONE	110-12-3	114.00	0.80	4.50	5400	1.20E-04	0.00E+00	0.00E+00	144.0	0	0	0
METHYL ISOBUTYL KETONE	108-10-1	100.2	0.80	15.7	19000	4.95E-05	7.80E-06	7.50E-02	115.8	6.672	1168.4	191.9
METHYL ISOCYANATE	624-83-9	57.05				0.00E+00						
METHYL ISOPROPYL KETONE	563-80-4	86.13			47000	4.50E-04						
METHYL METHACRYLATE	80-62-6	100.10	0.95	39		6.60E-05	8.60E-06	7.70E-02	101.0	8.409	2050.5	274.4
METHYL NAPTHALENE(1-)	90-12-0	142.19		0.1		7.10E-04	0.00E+00	0.00E+00	241.5			
METHYL NAPTHALENE(2-)	91-57-6	142.19		0.0088		5.80E-05	0.00E+00	0.00E+00	241.5			
METHYL SULFURIC ACID	468	112.10			20000	5.60E-07						
METHYL SULFURIC ACID		112.1		3	100000							
METHYLACRYLONITRILE	126-98-7	67.10		86	25	3.30E-01						
METHYLAMINE	74-89-5	31.06		1520	11500	6.30E-08						
METHYLAMINOACETYLENE	84	54.00			100	1.36E-01						
METHYLBIPHENYL (-p)	644-08-6	168.45			2	8.42E-03						
METHYLENE CHLORIDE	75-09-2	85.0	1.34	438		2.10E-03	1.17E-05	1.01E-01	39.8	7.409	1325.9	252.6
METHYLIMINODIACETIC ACID	64	100.00			10000	1.00E-08						
METHYLNAPHTHALENE (1)		142.2										
METHYLTIN TRICHLORIDE	993-16-8	240.08			100	2.40E-05						
METHYL(A)STYRENE DIMERS	6144-04-3	236.18			2	1.18E-02						
METHYL-2-AMINOETHYLAMINE	109-81-9	74.05			1000	1.88E-02						
METHYL-2-HYDROXYETHYLAMINE	109-83-1	75.11		0.7	20000	3.48E-08						
MHB	surrogate	69.9		1		6.60E-05	1.10E-05	9.90E-02				
MHLB	surrogate	112.0		1		2.32E-05	8.60E-06	7.60E-02				
MHMB	surrogate	57		1		4.09E-05	1.10E-05	1.16E-01				
MONOCHLORODIFLUOROMETHANE	75-45-6	86.50		7483	2	4.29E+02	0.00E+00	0.00E+00	-40.8			
MORPHOLINE	110-91-8	87.12	1.00	10	20000	5.70E-05	9.60E-06	9.10E-02	129.0	0	0	0
m-XYLYL CHLORIDE	620-19-9	140.60			10	1.41E-03						
NAPHTHALENE	91-20-3	128.2	1.14	0.23		1.18E-03	7.50E-06	5.90E-02	218.0	7.01	1733.71	201.86
NAPHTHOQUINONE-1,4	130-15-4	158.00	1.42	0.11111	1000	2.31E-05	0.00E+00	0.00E+00	100.0	0	0	0
NEOPENTYL GLYCOL	126-30-7	104.17			860000	1.60E-08						
NEOPRENE	9010-98-4	100000.00	1.23	0.001	2		0.00E+00	0.00E+00	59.4	0	0	0
NIACIN	59-67-6	123.12			20000	6.10E-07						
NIACINAMIDE	98-92-0	122.14			10000	1.22E-08						
NICKEL CYANIDE												

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NITROANILINE(-o)	88-74-4	138.14	1.44	0.008		6.00E-07	8.00E-06	7.30E-02	284.1	8.868	3336.80	0
NITROBENZENE	98-95-3	123.1	1.20	0.3		1.31E-05	8.60E-06	7.60E-02	210.8	7.115	1746.8	201.8
NITROCELLULOSE	9004-70-0	10000.00			10	1.00E-08						
NITROGLYCERIN	55-63-0	227.09	1.60	0.0026		8.00E-10	0.00E+00	0.00E+00	260.0	0	0	0
NITROMETHANE	75-52-5	61.05		27.8	95	2.86E-05						
NITROPHENOL(4)	100-02-7	139.00	1.40	0.666	16	8.34E-06	0.00E+00	0.00E+00	279.0	0	0	0
NITROSOMORPHOLINE		116.14					1.00E-05	6.80E-02	225			
NITROTOLUENE (-p)	99-99-0	137.13		1	442	4.08E-04						
N,N-DIMETHYL BENZYLAMINE	103-83-3	135.20			10	1.36E-08						
N,N-DIMETHYL METHYLTHIOCARBAMATE		119		8	2000							
N,N-DIETHYL NITROISOPROPYLAME	612	130.00			80	2.66E-04						
n-HEXADECANE	544-76-3	226.30			0.0009	2.52E+01						
N-HYDROXYMETHYLPHENYL CARBAMAT	471	169.00			1000	1.86E-05						
N-HYDROXYMETHYL, N-METHYLETHYL	611	89.00			80	4.46E-01						
N-HYDROXYMETHYL-N-CHLOROMETHYLETHYLAMINE		109.5		8	80							
N-METHYLCHLOROACETAMIDE	481	107.50			1000	1.08E-06						
N-METHYLPHENYL CARBAMATE	472	140.00			1000	1.40E-06						
N-METHYL, N-PHENYLETHYLAMINE	589-08-2	135.23			10	1.36E-08						
N-METHYL-2,3,4-TRIHYDROQUINOLI	478	148.00			1000	1.40E-06						
N-NITROSOPYRROLIDINE	930-55-2	100.12			2	1.36E-01						
N-NITROSO-N-METHYLUREA	684-93-5	103.10			2	6.16E-05						
N-SUBST-ALKOLIDINE CARBOXYLIC	482	200.00			2000	1.00E-06						
n-TRIDECANE	629-50-5	184.31			2	9.22E-05						
OCTANE	111-65-9	114.20	0.70	17	0.66	3.07E+00	0.00E+00	0.00E+00	125.7	6.918	1351.99	209.15
OCTYL ALCOHOL	111-87-5	130.20		0.124	300	4.34E-05						
OXALIC ACID	144-62-7	90.04			10000	4.80E-09						
OXAMIC ACID	471-47-6	89.06	89.1		100	8.90E-05						
O,O-DIETHYL O-2-ETHYLTHIOETHYL	126-75-0	258.36		1.300E-18	2	2.21E-14	0.00E+00	0.00E+00	549.6			
O-CHLORONITROBENZENE	88-73-3	157.56			2	7.88E-06						
O-ETHYL S,S-DIPHENYL PHOSPHORODI	17109-49-8	310.39			2	1.66E-04						
O-POLYCYCLIC KETO	510	1000.00			2	6.00E-02						
O-XYLYL CHLORIDE	552-45-4	140.60			10	1.41E-08						
PARAFORMALDEHYDE	30525-89-4	1000.00			100	1.00E-08						
PARALDEHYDE	123-63-7	132.20	0.99	25.3	120000	3.07E-05	0.00E+00	0.00E+00	126.0	0	0	0
PARATHION	56-38-2	291.30	1.20	0.008		4.80E-06	0.00E+00	0.00E+00	375.0			

COMPOUND NAME	CAS #	M.W.	DENSITY (g/cc)	VAP.PRESS (mmHg)	SOLUBILITY (mg/l)	H LAW CONST. (atm-m3/mol)	DIFF.WATER (cm2/sec)	DIFF.AIR (cm2/sec)	BOILING POINT (deg.C)	VAPOR PRESSURE COEFFICIENTS A	B	C
PARA-CHLOROFLUOROBENZENE	352-33-0	130.00			0.2	1.60E+02						
PARA-CHLOROTHIOPHENOL	106-54-7	144.62			0.2	7.35E-02						
PARA-NITROANILINE	100-01-6	138.14		1	800	2.27E-04						
PARA-XYLYL CHLORIDE	104-82-5	140.61			10	1.41E-03						
PCB-1254	11097-69-1	326.10	1.11	0.00008	0.08	2.80E-04	0.00E+00	0.00E+00	0.0	0	0	0
PENTACHLOROBENZENE	608-93-5	250.34	1.83	0.0046		7.30E-03	6.30E-06	5.70E-02	277.0	0	0	0
PENTACHLOROETHANE	76-01-7	202.30	1.67	4.4		2.10E-02	7.30E-06	6.60E-02	162.0	6.740	1378	197
PENTACHLOROPHENOL	87-86-5	266.40	1.98	0.00009		2.80E-06	6.10E-06	5.60E-02	310.0	0	0	0
PENTAERYTHRITOL	115-77-5	136.15		5	56000							
PENTAERYTHRITOL TETRANITRATE	78-11-5	316.17			10	3.16E-05						
PHENACETIN	62-44-2	179.24	0.00	0.00072	760	2.23E-07	0.00E+00	5.70E-02	300.0	0	0	0
PHENANTHRENE	85-01-8	178.22	1.18	0.00021		6.05E-05	0.00E+00	0.00E+00	340.0			
PHENOL	108-95-2	94.1	1.07	0.341		4.54E-07	9.10E-06	8.20E-02	182.0	7.133	1516.79	174.95
PHENOL, 2,4-DINITRO-6-(1-METHY	88-85-7	240.24			50	1.20E-08						
PHENOTHIAZINE	92-84-2	199.28			1	1.90E-02						
PHENYL ISOCYANATE	103-71-9	119.12			1	1.10E-02						
PHENYL MERCURIC ACETATE	62-38-4	336.70				1.20E-09						
PHENYLACETIC ACID	103-82-2	136.14			10000	8.30E-07						
PHENYLACETIC PEROXIDE	78	182.00			1000	1.62E-05						
PHENYLENE DIAMINE(-m)	108-45-2	108.14	1.14	0.038		1.10E-09	0.00E+00	0.00E+00	284.0	0	0	0
PHENYLENE DIAMINE(-o)	95-54-5	108.14	0.00	0.00787		1.10E-09	0.00E+00	0.00E+00	258.0	0	0	0
PHENYLENE DIAMINE(-p)	106-50-3	108.14	0.00	0.0046		1.10E-09	0.00E+00	0.00E+00	267.0	0	0	0
PHENYLHYDRAZINE	100-63-0	108.16			100	1.08E-04						
PHORATE	298-02-2	260.40		84.7		4.37E-07			110.6			
PHOSGENE	75-44-5	98.92	0.00	1394		1.71E-02	1.12E-05	1.08E-01	8.1	6.842	941.25	230
PHOSPHINE	7803-51-2	34		2000	100	8.96E-01						
PHTHALIC ACID	88-99-3	166.14	1.59	130.8	3000	1.32E-02	6.80E-06	6.40E-02	72.6	0	0	0
PHTHALIC ANHYDRIDE	85-44-9	148.1	1.53	0.0015		9.00E-07	8.60E-06	7.10E-02	284.0	8.022	2868.5	0
PHTHALIMIDE	85-41-6	147.10		117.6	2000	1.14E-02	0.00E+00	0.00E+00	89.6			
PICOLINE(2-)	109-06-8	93.12	0.95	10.4	10000	1.27E-04	9.80E-06	7.50E-02	129.8	7.032	1415.73	211.63
PINENE(alpha-)	80-56-8	136.20	0.86	5	2	4.48E-01	0.00E+00	0.00E+00	155.0			
PIPERAZINE	110-85-0	86.14	0.00	3.72	10000	4.22E-05	0.00E+00	8.10E-02	146.0	0	0	0
POLYBUTADIENE	582	1000.00			0.2	5.00E-08						
POLYCHLORINATED BIPHENYLS		290	1.46			2.94E-04	1.00E-05	1.04E-01				
POLYETHYLBENZENE	587	1600.00			0.2	7.50E-08						
POLYETHYLENE	[illegible]	[illegible]										

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POLYMERS CONTAINING NITROGEN	870	8000.00			0.2	2.80E-02						
POLYPROPYLENE	9003-07-0	20000.00			0.2	1.00E-01						
POLYSTYRENE	9003-53-6	30000.00			100	2.00E-04						
POLYURETHANE	870	20000.00			0.2	1.00E-01						
POLYVINYL ACETATE	9003-20-7	128000.00			0.2	6.25E-01						
POLYVINYL ALCOHOL	9002-89-5	130000.00			30000	6.00E-08						
POLYVINYL CHLORIDE	786	20000.00			0.2	1.00E-01						
POLYVINYLIDENE CHLORIDE	874	20000.00			0.2	1.00E-01						
PROPANE	74-98-6	44.09		760	2000	2.30E-02						
PROPIONALDEHYDE	123-38-6	58.08	0.81	300	20000	1.16E-03	1.14E-05	1.02E-01	49.6	0	0	0
PROPIONIC ACID	79-09-4	74.08		10	20000	4.87E-05						
PROPIONITRILE	107-12-0	55.08		40	60000	2.76E-04						
PROPYLENE	115-07-1	42.08		7600	200	2.11E+00						
PROPYLENE GLYCOL	57-55-6	76.11	1.04	0.2	20000	1.30E-08	1.02E-05	9.30E-02	188.0	0	0	0
PROPYLENE OXIDE	75-56-9	58.1	0.83	524.5	20000	1.34E-08	1.00E-05	1.04E-01	33.9	2.710040		
PROPYL(-n) ACETATE	109-60-4	102.13	0.89	35	18000	2.94E-04	0.00E+00	0.00E+00	101.6	7.016	1282.28	208.60
PROPYL(-n) BENZENE	103-65-1	120.19	0.86	2.5	60	6.66E-03	0.00E+00	0.00E+00	159.0	0	0	0
PYRENE	129-00-0	202.30	1.27	0.00000000	2	7.02E-09	0.00E+00	0.00E+00	404.0			
PYRIDINE	110-86-1	79.1	0.98	20	30000	2.36E-05	9.30E-06	9.30E-02	115.5	7.041	1373.8	214.98
PYRIDINIUM BROMIDE	885	160.00			20000	1.46E-08						
P,P'-DIAMINODIPHENYLMETHANE	101-77-9	198.28		3	100							
p,p'-DICHLOROBENZOPHENONE	90-98-2	251.11		0.000000087	0.2	4.74E-08			353.0			
p-AMINO-p'-METHYLAZOBENZENE	126	212.00			2	1.08E-08						
p-CHLOROBENZOPHENONE	134-85-0											
p-CHLOROBENZOTRICHLORIDE	5216-25-1	230.87			0.2	1.16E-01						
p-CHLORODIPHENYL THIOETHER	7005-72-3	204.57			2	1.00E-02						
p-CHLOROMETHYL BENZOATE	1126-46-1	170.60			0.2	6.53E-02						
p-CHLOROMETHYL PHENYLHYDRAZINE	62	157.00			60	3.14E-04						
p-CHLORO-N-METHYLBENZAMIDE	479	169.61			3000	6.46E-08						
p-CHLORO-p'-METHYLBIPHENYL	1667-11-4	202.68			2	1.01E-02						
p-CYANOBENZYL ALCOHOL	118	119.00			8000	2.38E-08						
p-DIETHYLBENZENE	25340-17-4	134.22			2	6.71E-08						
p-METHOXYPHENOL	150-76-5	124.15			40000	3.10E-07						
p-METHYL-p'-METHYLTRIPHENYL PH	208	292.30			2	1.46E-02						
p-NITROBENZENESULFONYL CHLORIDE	98-74-8	221.63			50	[illegible]						

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p-PHENYLPHENOL	92-69-3	170.20		10	700	3.30E-08						
p-THIOBENZYL ALCOHOL	100-53-8	194.21			1000	1.34E-05						
p-TOLUIDINE	106-49-0	107.17		1	7400	1.90E-05						
RESERPINE	50-55-5	608.70	0.00	0.0052	2	2.09E-08	0.00E+00	8.30E-02	205.0	0	0	0
RESORCINOL	108-46-3	110.11	0.00	0.00088	2000	1.80E-09	8.70E-06	7.80E-02	280.0	0	0	0
SIMAZINE	122-34-9	201.70		0.00000000	5	8.00E-10						
SODIUM ACETATE	784	82.04			20000	4.30E-09						
SODIUM DODECYLBENZENE SULFONATE	25155-30-0	348.10			20	1.40E-05						
SODIUM FORMATE	141-53-7	68.01			40000	1.70E-09						
STRYCHNIDIN-10-ONE,2,3-DIMETHOXY	357-57-3	394.45			87000	1.40E-09						
STYRENE	100-42-5	104.20	0.90	7.3		2.80E-03	8.00E-06	7.10E-02	145.0	7.140	1574.51	224.09
SUCCINIC ACID	110-15-6	118.09			80000	1.74E-09						
SUCCINIMIDE	123-56-8	99.10			300000	3.30E-09						
SULFANILIC ACID	121-47-1	173.20			10800	1.60E-09						
SULFURIC ACID	7664-93-9	98.08	0.00	0.001	20000	6.40E-09	1.80E-05	1.10E-01	0.0	0	0	0
SYM-DIETHYLDIPHENYL UREA	85-98-3	268.36			2	1.34E-02						
S,S,S-TRIBUTYL PHOSPHOROTRITHIOATE	78-48-8	314.54			2	1.57E-04						
S-4-CHLOROCYCLOHEXYL-O,O-DIMET	846	348.00			2	1.79E-04						
S-CYCLOHEXYL o,o-DIMETHYL PHOSPHORODITHIOATE		240		4	2							
S-ETHYLSULFINYLMETHYL o,o-DIISOPROPYL PH		330		4	2							
S-ETHYLSULFINYLMETHYL O,O-DIISOPROPYL-03-4		304.45			2	1.62E-04						
TARS	888	400.00			0.2	2.00E-08						
TETRACHLOROQUINONE		246		2	2							
TETRACHLOROBENZENE(1,2,3,4)	634-66-2	215.90	0.00	0.089	2	2.70E-03	0.00E+00	0.00E+00	254.0	0	0	0
TETRACHLOROBENZENE(1,2,3,5)	634-90-2	215.90	0.00	0.08	2	4.20E-03	0.00E+00	0.00E+00	246.0	0	0	0
TETRACHLOROBENZENE(1,2,4,5)	95-94-3	215.90	1.86	0.08	2	4.20E-03	0.00E+00	0.00E+00	240.0	0	0	0
TETRACHLOROETHANE(1,1,1,2)	630-20-6	168.00	1.60	6.5		2.00E-03	7.90E-06	7.10E-02	146.3	6.898	1365.88	209.74
TETRACHLOROETHANE(1,1,2,2)	79-34-5	168.0	1.59	6.5		3.80E-04	7.90E-06	7.10E-02	146.2	6.631	1228.1	179.9
TETRACHLOROETHENE	127-18-4	165.83	1.624	19	-	2.30E-02	8.20E-06	7.20E-02	121.4	6.976	1386.92	217.53
TETRACHLOROPHENOL(2,3,4,6)	58-90-2	231.90	0.00	0.80		4.50E-06	0.00E+00	0.00E+00	164.0	0	0	0
TETRACHLOROPHENOL(2,3,5,6)	935-95-5	231.90	0.00	.01	2	1.11E+02	0.00E+00	0.00E+00	28.1	0	0	0
TETRACHLOROPROPENE (1,1,2,3)	10436-39-2	179.86			2	3.90E-03						
TETRAETHYL LEAD	78-00-2	323.45		0.15		6.00E-02						
TETRAETHYLDITHIOPYROPHOSPHATE	3689-24-5	322.34		0.00000018	30	7.60E-09						
TETRAETHYLENE GLYCOL	112-60-7	194.26		1	20000	1.20E-05						

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THIOSEMICARBAZIDE	79-19-6	91.14		0.01	20000	4.00E-08						
THIOUREA	62-56-6	76.12	1.41	146		1.40E-04	0.00E+00	1.07E-01	182.0	0	0	0
TOLUENE	108-88-3	92.4	0.87	30		6.60E-03	8.40E-06	8.70E-02	110.7	6.954	1344.8	219.48
TOLUENE DIAMINE(2,4)	95-80-7	122.00	1.11	0.001	3000	8.00E-08	0.00E+00	0.00E+00	0.0	0	0	0
TOLUENE DIISOCYANATE(2,4)	584-84-9	174.16	1.20	0.08		8.30E-06	8.30E-06	6.10E-02	251.0	0	0	0
TOLUENE-2,4-DIAZO-BIS-META-TOL.	159	428.00			1000	4.38E-05						
TOLUIC ACID (para-)	99-94-5	136.16		0.00081		5.80E-08	0.00E+00	0.00E+00	275.0			
TOLUIC ALDEHYDE	122-78-1	120.14	1.08	0.16	300	2.50E-04	0.00E+00	0.00E+00	204.0			
TOLUIDINE (-O)	95-53-4	107.17		0.342								
TOXAPHENE	8001-35-2	414.00	1.11	0.2		4.89E-06	0.00E+00	0.00E+00	0.0	0	0	0
TRIBROMOMETHYLPHOSPHATE	844	348.67			10	3.47E-05						
TRICHLOROBENZENE(1,2,4)	120-82-1	181.50	0.00	0.18		1.42E-03	0.00E+00	0.00E+00	213.0	0	0	0
TRICHLOROBENZENE(1,3,5)	108-70-3	181.50	0.00	0.29		2.08E-02	0.00E+00	0.00E+00	208.5	0	0	0
TRICHLOROBUTANE(1,2,3)	18338-40-4	161.46	0.00	4.36	0.2	4.00E+00	7.30E-06	6.60E-02	0.0	0	0	0
TRICHLOROETHANE(1,1,1)	71-55-6	133.4	1.38	123		1.72E-02	8.80E-06	7.80E-02	75.0	8.643	2136.6	302.8
TRICHLOROETHANE(1,1,2)	79-00-5	133.4	1.4	25		7.42E-04	8.80E-06	7.80E-02	74	6.951	1314.4	209
TRICHLOROETHYLENE	79-01-6	131.4	1.46	75		9.10E-03	9.10E-06	7.90E-02	87.0	6.518	1018.6	192.7
TRICHLOROFLUOROMETHANE	75-69-4	137.4	1.49	796		5.83E-02	9.70E-06	8.70E-02	23.8	6.884	1043.004	236.88
TRICHLOROPHENOL(2,4,6)	88-06-2	197.46	0.00	0.0073		1.77E-05	0.00E+00	0.00E+00	244.5	0	0	0
TRICHLOROPROPANE(1,1,1)	7789-89-1	147.43	0.00	3.1		2.80E-02	7.90E-06	7.10E-02	107.0	0	0	0
TRICHLOROPROPANE(1,1,2)	598-77-6	147.43		3.84		2.80E-02			140.0			
TRICHLOROPROPANE(1,2,2)	3175-23-3	147.38		1.37		2.80E-02			124.0			
TRICHLOROPROPANE(1,2,3)	96-18-4	147.43	0.00	3		2.80E-02	7.90E-06	7.10E-02	156.0	6.903	788.2	243.23
TRICHLOROPROPENE (1,1,2)	653	145.40			2	7.27E-06						
TRICHLORO(1,1,2)TRIFLUOROETHANE	76-13-1	187.38	1.58	300		4.36E-01	8.20E-06	7.80E-02	48.0	6.88	1099.9	227.5
TRIETHYLAMINE	121-44-8	101.22		400	20000	2.08E-05						
TRIETHYLENE GLYCOL	112-27-6	150.20		1	20000	9.80E-09						
TRIFLUOROETHANE(1,1,1)	456	84.00		8041	2	9.40E+01			-47.3			
TRIMELLITIC ANHYDRIDE	552-30-7	192.13		0.0001		4.30E-06	0.00E+00	0.00E+00	242.5			
TRIMETHYLAMINE	75-50-3	59.11		1	100000							
TRIMETHYLBENZENE (1,3,5)	108-67-8	120.20		1.86	2	1.47E-01						
TRINITROTOLUENE(2,4,6)	118-96-7	227.10		0.046	1000	1.37E-06						
TRIPHENYL PHOSPHINE	603-35-0	262.30			2	1.31E-04						
TRIPHENYLPHOSPHINE NICKEL CARB	287	377.00			10	3.77E-08						
UREA	57-13-6	60.06	1.34	6.69	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			

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VALERIC ACID	109-52-4	102.13		1	3000	8.73E-05						
VINYL ACETATE	108-05-4	86.09	0.93	115		6.20E-04	9.20E-06	8.50E-02	73.0	7.210	1296.13	226.66
VINYL CHLORIDE	75-01-4	62.5	0.91	2660		8.67E-02	1.23E-05	1.06E-01	-13.9	[illegible]		
VINYLIDENE CHLORIDE		97.0	1.21	591		1.50E-01	1.04E-05	9.01E-02	31.9	6.972	1099.4	237.2
XYLENE	1330-20-7	106.20		8.5		5.30E-03						
XYLENE(-m)	108-38-3	106.16	0.86	8		6.30E-03	7.80E-06	7.00E-02	139.0	7.009	1426.266	215.11
XYLENE(-o)	95-47-6	106.2	0.88	7		5.27E-03	1.00E-05	8.70E-02	144.4	6.998	1474.679	213.69
XYLENE(-p)	106-42-3	106.16	0.86	6.5		6.27E-03	0.00E+00	0.00E+00	138.4	6.990	1453.430	215.31
ZINC ACETATE	000	183.46			30000	6.17E-09						

Table 2. Default Values for Compound Properties

Compound type	Code	Molecular weight	Density, g/cc	Vapor pressure, mm Hg	Henry's law constant, atm-m^3/mol	Diffusion in liquid, cm^2/sec	Diffusion in vapor, cm^2/sec	Biorate volume, mgVO/g-hr	K1, L/g-hr
General	0	100	1	12	0.0003	0.000000	0.000	15.3	1.0
Aromatic	A	106	1.02	4.1	0.0110	0.000000	0.070	31.1	1.00
Biphenyl	B	223	1.19	2.9	0.0073	0.000000	0.081	19.0	0.96
Chlorinated	C	176	1.41	693.0	10.60	0.000000	0.083	10.70	1.70
Hydrocarbon	H	104	0.78	600.0	3.5	0.000000	0.100	15.3	1.0
Inorganic	I	76	1.00	0	0	0.000000	0.000	0	0
Metal	M	240	1.05	80.0	0.0073	0.000000	0.000	0	0
Nitrogen	N	194	1.16	100.0	0.1933	0.000012	0.110	9.7	5.02
Oxygenate	O	120	0.97	142.0	0.0072	0.000010	0.110	17.60	4.40
Pesticide	P	282	1.10	10.0	4,420.0	0.000000	0.000	15.3	2.03
Sulfur	S	121	1.20	192.0	0.0200	0.000010	0.100	15.3	2.03

APPENDIX G

PHYSICAL AND CHEMICAL PROPERTY DATA FOR 25 COMPOUNDS OF POTENTIAL CONCERN AND FOR COMPOUND CLASSES

APPENDIX G.

CHEMICAL AND PHYSICAL PROPERTIES FOR 25 COMPOUNDS OF POTENTIAL CONCERN

No.	Compound	Henry's Law Constant (atm-m/mol)	Henry's Law Constant (atm-m3/gmol)	Henry's Law Constant (atm) @20 C	log Kow (octanol-water partition coeff (@ 25 C)	Flash Point (C)	Vapor Density	Maximum Water Solubility mg/L	V-L Equil. Constant K
1	Acetone		2.50E-05		-0.24	-18	2	1000000	
2	Acrylonitrile		8.80E-05		-0.92	0	1.83	79000	
3	Benzene	0.00550	5.50E-03	2.40E+02	2.13 @ 20 C	-11	2.77	1750	61.9
4	Carbon Tetrachloride	0.03020	3.00E-02	1.29E+03	2.83	non-flam	5.3	757	313.1
5	Chlorobenzene	0.0039	3.93E-03		2.84 @ 20 C	23	3.88	466	40.8
6	Chloroform	0.0039	3.39E-03	1.70E+02	1.97 @ 20 C	non-flam	4.12	8200	49
7	Dichlorobenzene, o-		1.94E-03		3.38	66	5.05	100	
	Dichlorobenzene, m-		3.61E-03		3.38	63	5.08	123	
	Dichlorobenzene, p-		1.60E-03	1.90E+02	3.39	65.5	5.08	790	
8	1,1 Dichloroethane	0.0056	5.54E-03		1.79	-5	3.44	5500	71.3
9	1,2 Dichloroethane	0.0014	1.20E-03	6.10E+01	1.48	13	3.4	8520	17.1
10	Ethylbenzene		6.44E-03		3.15	15	3.66	152	
11	Isopropyl Alcohol		1.50E-04		-0.16/0.28 calc	12	2.07		
12	Methylene Chloride	0.0032	2.24E-03		1.25	non-flamm@<	2.93	20000	49.8
13	Methyl Ethyl Ketone		4.35E-05		0.26	-3	2.42	268000	
14	Methyl t-Butyl Ether		7.80E-04		1.74+-0.12	-28			
15	Napthalene		1.18E-03		3.01/3.45	88	4.42		
16	Phenol		4.54E-07		1.46	79	3.24	93000	
17	Tetrachloroethylene		2.90E-02	1.10E+03	2.60 @ 20 C	non-flam	5.83	150	
18	Toluene		6.68E-03	3.40E+02	2.73	4.4	3.14	535	
19	1,1,2 Trichloroethane	0.0049	7.40E-04	4.30E+01	2.47	non-flam	4.63	4500	48.7
20	1,1,1 Trichloroethane		1.72E-02	4.00E+02	2.5	non-flam	4.6	1500	
21	Trichloroethylene		9.10E-03	5.50E+02	2.29	non-flam	4.53	1100	
22	Vinyl Chloride	0.19000	8.60E-02	3.55E+05	1.38	-78.9	2.15	2670	2760.3
23	o-Xylene		5.27E-03		2.77	17.1	3.66	175	
4	m-Xylene		5.20E-03		3.2	29.4	3.66	130	
5	p-Xylene		5.27E-03		3.15	27.2	3.66	198	

APPENDIX G.

CHEMICAL AND PHYSICAL PROPERTIES FOR 25 COMPOUNDS OF POTENTIAL CONCERN

No.	Compound	Molecular Weight	Boiling Point (C)	Vapor Pressure (mm Hg)	Diffusivity in Water (cm2/sec) x10E-05	Liquid Density (g/cm3)	Odor Threshold (ppm)	Diffusivity in Air (cm2/sec)
1	Acetone	58.08	56.2	266	1.1400	0.790	100	0.1240
2	Acrylonitrile	53.06	77.4	114	1.3400	0.810	21.4	0.1220
3	Benzene	78.12	80.1	95.2	0.9940	0.879	0.84	0.0932
4	Carbon Tetrachloride	153.82	76.7	113	0.8840	1.595	21.4	0.0632
5	Chlorobenzene	112.56	131.6	11.8	0.9000	1.170	0.21	0.0730
6	Chloroform	119.38	61.2	208	1.0600	1.489	675	0.0888
7	Dichlorobenzene, o-	147.00	179.0	1.5	0.7900	1.310	2-4	0.0690
	Dichlorobenzene, m-	147.00	172.0	2.28	0.7860	1.290	0.02	0.0692
	Dichlorobenzene, p-	147.00	173.4	1.2	0.7900	1.290	15-30	0.0690
8	1,1 Dichloroethane	98.96	57.0	234	0.9880	1.256	120	0.0919
9	1,2 Dichloroethane	98.96	83.5	80	0.9880	1.256	3-100	0.0907
10	Ethylbenzene	106.16	136.2	10	0.7800	0.870	0.46-0.60	0.0750
11	Isopropyl Alcohol	60.09	82.4	42.8	1.0400	0.790	7.5	0.0980
12	Methylene Chloride	84.93	40.1	400	1.6600	1.327	25-307	0.1000
13	Methyl Ethyl Ketone	72.11	79.6	100	0.9800	0.820	2	0.0808
14	Methyl t-Butyl Ether	88.15	55.0	245	0.8026	0.758		0.0806
15	Napthalene	128.19	218.0	0.023	0.7500	1.140	0.003	0.0590
16	Phenol	94.10	182.0	0.0341	0.9000	1.070	0.016	
17	Tetrachloroethylene	165.83	121.0	19	0.8200	1.624	50	0.0720
18	Toluene	92.14	110.7	30	0.8600	0.840	0.17	0.0870
19	1,1,2 Trichloroethane	133.41	113.7	25	0.8800	1.320		0.0792
20	1,1,1 Trichloroethane	133.41	75.0	123	0.8800	1.330	100	0.0780
21	Trichloroethylene	131.40	86.7	75	0.9100	1.400	21.4	0.0790
22	Vinyl Chloride	62.50	-13.9	2660	1.0400	0.908	260	0.0900
23	o-Xylene	106.20	144.0	7	1.0000	0.880	0.17	0.0870
4	m-Xylene	106.20	138.8	8	0.7800	0.860	-1	0.0700
5	p-Xylene	106.20	138.5	9.5		0.860	-0.3	